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MK 11 AND MK 12 CO2 SCRUBBER DEVELOPMENT.(U)
AUG 80 R W DOWGUL
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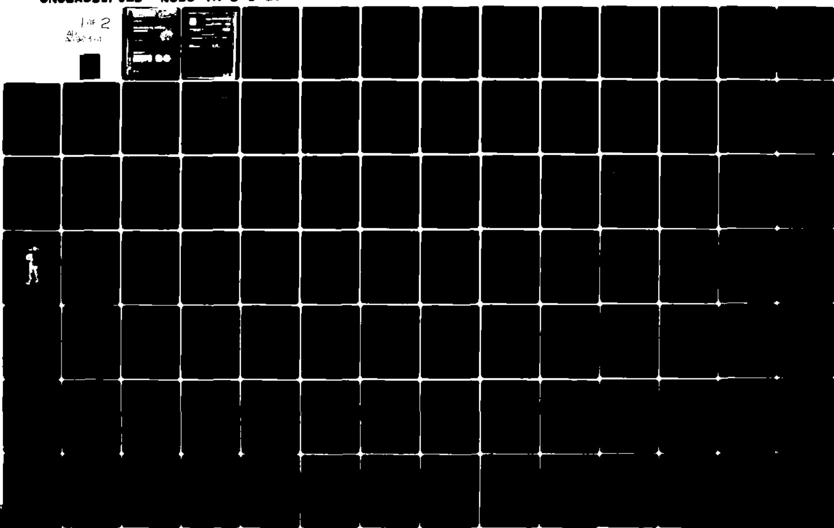

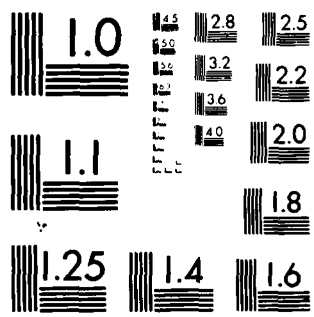

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Empirical testing is a major development tool in the design of CO_2 scrubbers used in diving systems. Suitable analytical models for predicting CO_2 scrubber behavior are currently under consideration. This report documents the development of CO_2 scrubbers for the MK 11 and MK 12 diving systems. Plots of various temperatures, pressures, flows, and system efficiencies are presented. For specific details Hydrospace notes and/or NEDU manned test reports are referenced where applicable.

ABSTRACT

Empirical testing is a major development tool in the design of CO_2 scrubbers used in diving systems. Suitable analytical models for predicting CO_2 scrubber behavior are currently under consideration. This report documents the development of CO_2 scrubbers for the MK 11 and MK 12 diving systems. Plots of various temperatures, pressures, flows, and system efficiencies are presented. For specific details Hydrospace laboratory notes and/or NEDU manned test reports are referenced where applicable.

GLOSSARY

ACFM	Actual cubic feet per minute. A measure of the volume of gas at operating temperature and pressure.
ALPM	Actual litres per minute. A measure of gas equal to 0.001 cubic metre per minute.
ATM	Atmosphere. A unit of pressure equal to 1.013250×10^6 dynes/cm^2, which is the air pressure at mean sea level (also known as standard atmosphere).
Baralyme	Granules that are used as a CO_2 absorbent.
BPM	Breaths per minute.
Cap Regulator	Constant absolute pressure regulator.
Cardiod Exhaust Valve	Attitude sensitive exhaust valve.
CDP	Constant Differential Pressure.
FSW	Feet of seawater.
Heliox	A mixture of helium and a small percent of oxygen used for breathing during deep dives.
High Performance Sodasorb	A mixture of sodium hydroxide with calcium oxide; granules are used to absorb water vapor and carbon dioxide gas.
LPM	Litres per minute.
PO_2	Partial pressure of oxygen.
PSID	Pounds per square inch differential. The difference in pressure between two points in a fluid flow system, measured in pounds per square inch (PSI).
PSIG	Pounds per square inch gauge. The gauge pressure, measured by the number of pounds/force exerted on an area of one square inch.
RMV	Respiratory minute volume.
SLE	Sea level equivalent. The equivalent level of the surface of the ocean; especially, the mean level halfway between high and low tide, used as a standard in determining sea depths.
STP	Standard temperature and pressure.
UBA	Underwater breathing apparatus.
WATTS	The unit of power in the metre-kilogram-second system of units, equal to 1 joule per second.

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INTRODUCTION

GENERAL

Carbon dioxide is a natural by-product of the respiration of animals and humans (among other sources) formed by the oxidation of carbon in the body to produce energy. It forms approximately 0.03 percent of the total atmosphere. For divers, the two major concerns with CO_2 are control of the quantity in the breathing supply, and removal of the "exhaust" after breathing.

In high concentrations the gas can be extremely toxic. Severe problems may arise for divers who use closed circuit and semi-closed circuit breathing systems, if the system fails to dispose of the excess CO_2.

The Navy has continuously worked on designing and improving techniques to eliminate carbon dioxide from the diver's gas supply.

The intent of the MK 11 and MK 12 CO_2 scrubber development is to maximize the efficiency of the CO_2 absorbent canisters. The flow of gas in these systems is through an absorbent canister where the carbon dioxide is removed. A constant flow of fresh CO_2-free gas ventilates the helmet or facemask for the diver to rebreathe. Since only the oxygen in the mix is consumed, assuming *his oxygen is replenished*, the diver can remain at depth for an extended period of time on relatively small amounts of inert gas. The inert gas is breathed and rebreathed repeatedly by the diver instead of exhausting from the helmet or facemask at the end of each exhaled breath.

The various systems, testing methods, and procedures of the CO_2 scrubber during empirical development are described in this report.

BACKGROUND

Mixed gas diving is differentiated from other techniques in that the breathing medium is a closely controlled mixture of oxygen and an inert gas such as helium. Helium-oxygen mixtures (Heliox) are preferred over other gas mixtures due to physiological and physical safety factors; however, helium is quite expensive, and methods to conserve helium usage are constantly being explored. CO_2 scrubbers permit rebreathing of the inert gas by removing the carbon dioxide from the breathing mix and circulating the gas freshened with O_2 back to the diver. This in turn reduces the expensive helium consumption and increases the capability to dive to deeper depths for a longer period of time.

Current development techniques for CO_2 scrubbers used in modern diving systems do not include suitable analytical models, therefore empirical testing is a major development tool.

MK 11 CO_2 Scrubber Development Results

The MK 11 CO_2 scrubber development terminated in a system that was man-tested at 450 feet (137.2 metres) of seawater (FSW) and 35°F (1.7°C) by the Navy Experimental Diving Unit (NEDU), Panama City, Florida. This resulted in a mean duration of 308(±42) minutes.

MK 12 CO_2 Scrubber Development Results

The MK 12 CO_2 scrubber development resulted in a system duration in excess of 10 hours at 390 FSW (118.9 metres) and 40°F (4.4°C). At a duration of 9 hours, the mean CO_2 level of the existing gas for three canisters was 0.2 percent sea level equivalent (SLE). One canister test was continued to 0.5 percent SLE which occurred at 10 hours.

MK 11 CO_2 SCRUBBER DEVELOPMENT

MK 11 SYSTEM DESCRIPTION

The MK 11 semi-closed mixed gas underwater breathing apparatus (UBA) and associated equipment was intended to provide the complete life support and thermal protection required for saturation divers to operate for up to 4 hours in 28°F (-2.2°C) water to depths of 850 FSW (259 metres). The MK 11 diver is tethered to a diver support facility by an umbilical which supplies breathing gas, hot water, and electrical connections. Hot water is routed through a breathing subsystem (Figure 1) where it warms a canister containing a carbon dioxide absorbent bed, and then is routed to a diver thermal protection garment (the MK 16 hot water suit).

During normal semi-closed circuit, umbilical-supplied operation, the breathing gas passes through an absolute pressure regulator block and sonic orifice into an inhalation bag, and then through a hose connection to an oral-nasal facemask. Exhaled gas passes from the oral-nasal mask via a hose to an exhalation bag. From the exhalation bag, most of the exhaled gas flows through the CO_2 scrubber to the inhalation bag where it is mixed with incoming gas from the umbilical, and subsequently, rebreathed. A portion of the exhaled gas does not pass through the canister but is exhausted into the water through an attitude-sensitive exhaust valve (cardioid valve).

Diver safety features include two-way communication equipment, a PO_2 sensor, and switchover indication equipment. If umbilical gas supply pressure drops to a low level, the absolute pressure regulator admits breathing gas from a small emergency supply in the backpack activating the switchover indicator. If the breathing bags or canister should flood, the diver can switch to open circuit on umbilical; or for a short time, the diver may use the

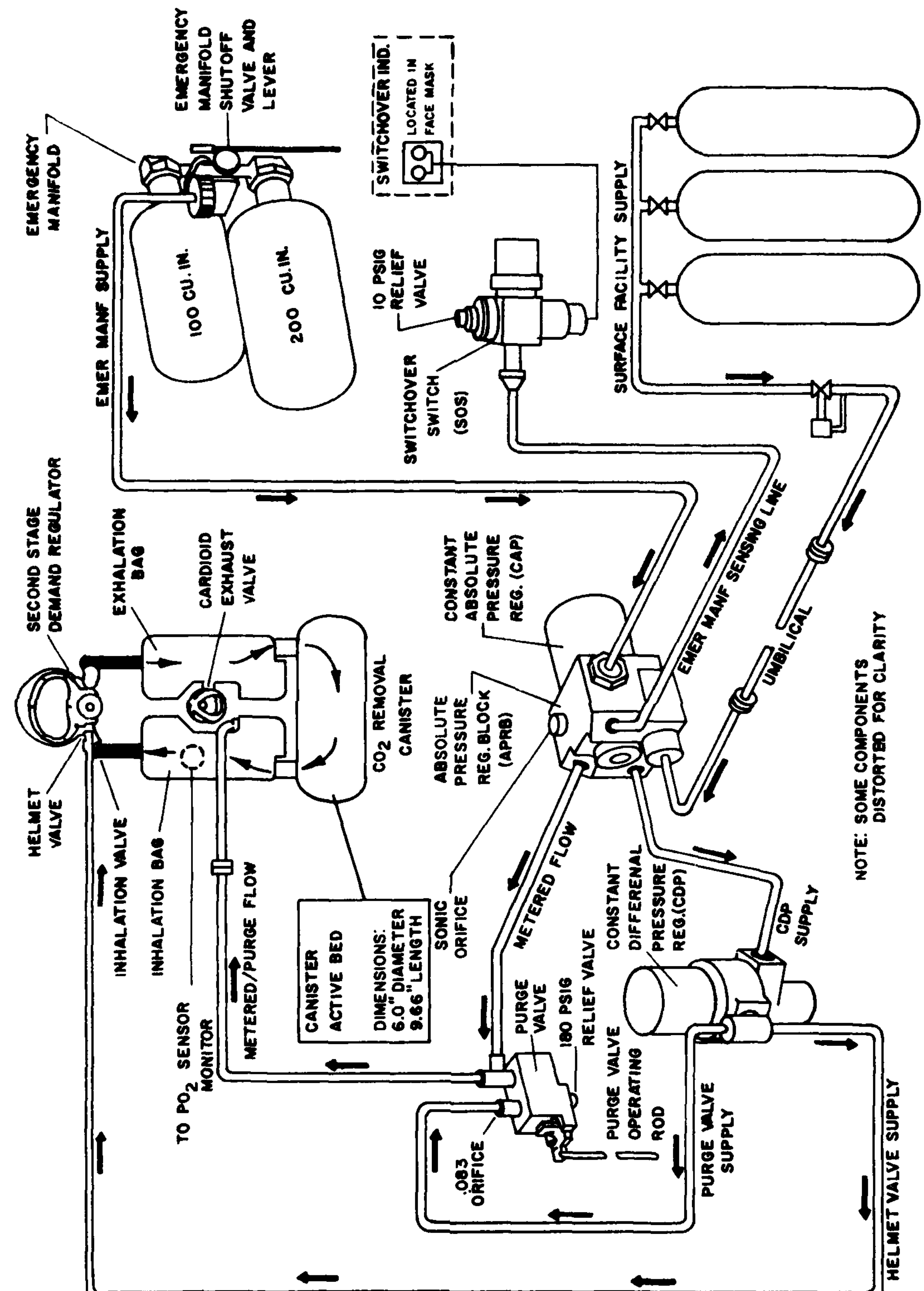

FIGURE 1. MK 11 BREATHING SUBSYSTEM

emergency gas supply. Therefore, a normal operating mode (semi-closed circuit, umbilical supply) and three backup modes (semi-closed circuit, emergency supply; open circuit, umbilical supply; and open circuit, emergency supply) are available to the diver (see Figure 2).

BACKGROUND

As a result of NEDU manned dives conducted during the week of 3 July 1978, it was found that the MK 11 CO_2 scrubber packed with baralyme was time-limited to approximately 1.5 hours at 305 FSW (92.9 metres) and 35°F (1.7°C). These short durations were revealed under NEDU work requirements utilizing repetitive 10 minute cycles consisting of 4 minutes at rest and 6 minutes of work at 50 watts as measured on an ergometer. Unmanned testing of various concepts and techniques to improve the CO_2 scrubber duration were conducted as a result of these short duration NEDU manned tests.

NOTE

Canister upstream CO_2 levels were recorded on subjects at depth in the MK 11 during rest and while registering 50 watts on an ergometer during manned dives. These CO_2 levels were then used as control parameters during unmanned testing.

	Rest	50 Watts	
% CO_2 SLE	3.45	4.69	
(Recorded)	22½ RMV	40 RMV	These were direct readings to give the percentage by volume. This is not a true temperature corrected flow at STP.
Unmanned Simulation	0.7 LPM CO_2 Injected	1.8 LPM CO_2 Injected	

INITIAL TESTING SUMMARY

A total of 31 tests were conducted in the Hydrospace Laboratory[1]. Results of these tests indicate that use of high performance sodasorb (special factory certified 18 percent water by weight), tightly packed in the canister while operating in 30°F (-1.1°C) water, resulted in an average run time of 3 hours and 51 minutes to reach a CO_2 level of 0.5 percent SLE. The absorbent was tightly packed by constantly tapping on the canister while slowly filling.

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[1] Hydrospace Laboratory Note 11-78, Index No. 64, *Underwater Breathing Apparatus - MK 11 Scrubber Test,* by G. H. Noble, August 1978.

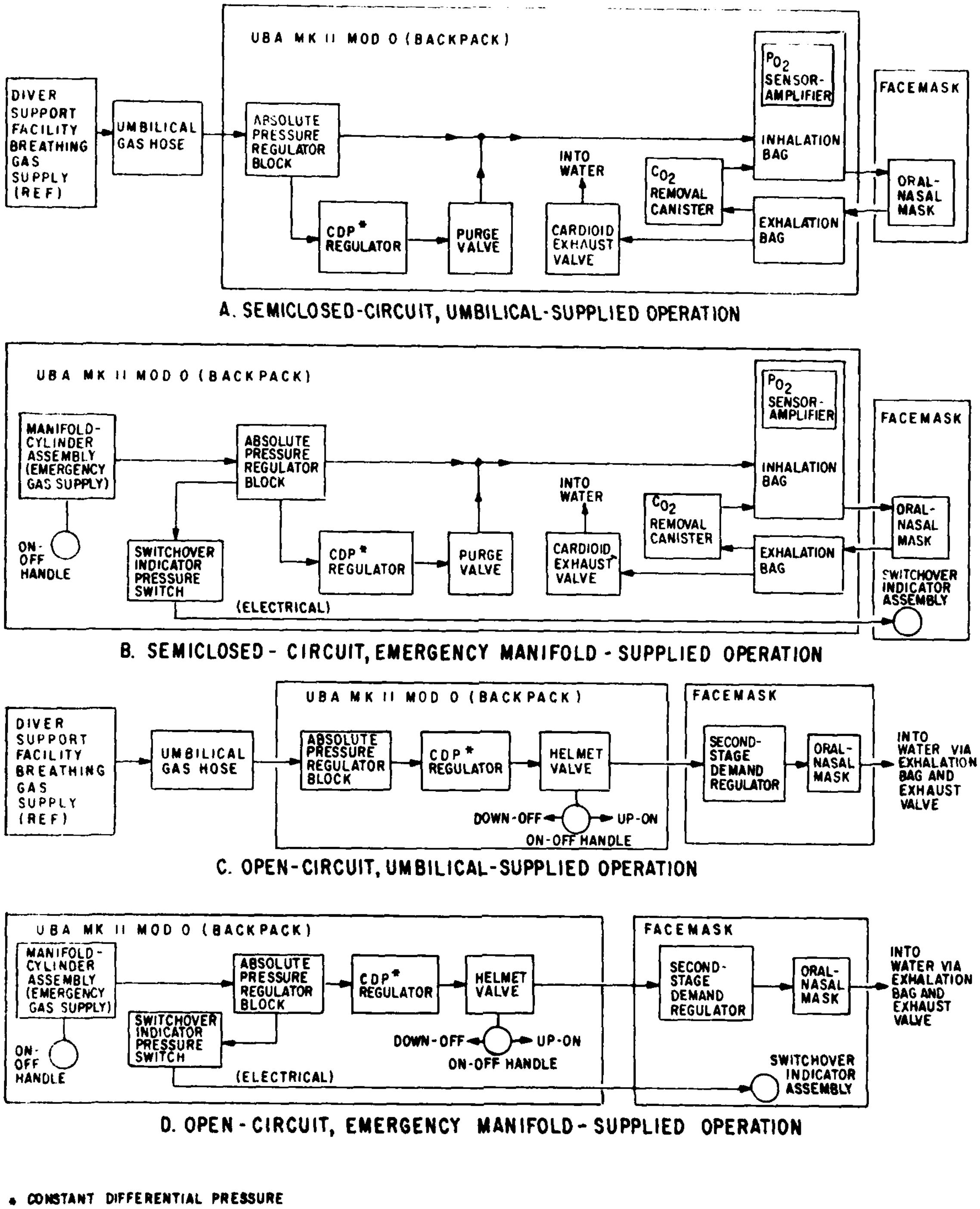

FIGURE 2. GAS FLOW DIAGRAM IN EACH OPERATING MODE

The test series began with little baseline data available other than the fact that the canister life was not adequate to meet test requirements during manned test dives. The test program was conducted in an attempt to provide an interim solution to the immediate problem and to build a file of baseline data. Preliminary indications were that the reduced canister life at depth resulted from a combination of system design shortcomings.

General Observations

Unmanned test results were bracketed by manned test results. Adequate correlation was obtained between the two types of tests (Figure 3).

PVC pipe was used to tap the canister during the filling process at the 1/3, 2/3, and full points. As an alternative, two hand-type electric massagers were strapped on the canister to provide vibration during the filling process in an attempt to improve packing of the bed and to reduce the sharp impact from tapping with a plastic pipe. The vibration resulted in a heavy accumulation of dust in the center of the bed. The absorbent particle distribution was believed to be caused by pulverizing of the grains and shifting of the larger grains to the perimeter. This method of packing was abandoned due to dust generated in the breathing loop.

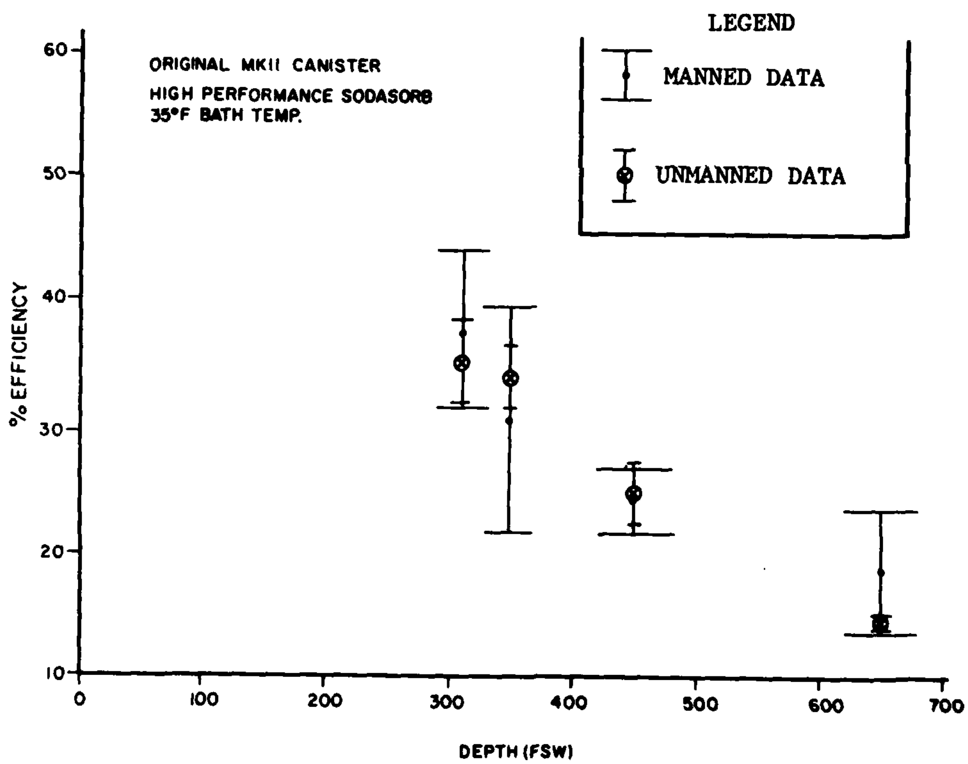

FIGURE 3. CANISTER EFFICIENCY VERSUS DEPTH (MANNED/UNMANNED)

The scrubber instrumentation diagram is shown in Figure 4. Figure 5 depicts typical unmanned canister bed temperatures of the MK 11 in the original configuration for baralyme and high performance sodasorb 92.9 MSW (305 FSW, 35°F (1.7°C) bath temperature). Figure 6 shows typical unmanned canister CO_2 signatures for baralyme and high performance sodasorb. Figure 7 presents typical manned canister bed temperatures of the MK 11 in the original configuration. Figure 8a presents the MK 11 manned CO_2 signature, and 8b shows the mean canister breakthrough curves at various depths using high performance sodasorb.

SYSTEM FLOW ANALYSIS OF MK 11

Background

Manned testing of the MK 11 at depth[(2)] and at 6 MSW (20 FSW)[3] revealed a marked difference in canister life (canister life was reduced at depth by over 85 percent). In an attempt to find the cause of this difference, a series of MK 11 system dynamic flow measurements were made at various depths and breathing rates.

Objective

The objective of this test series was to compare system flow at depths from 0 to 259 MSW (0 to 850 FSW)[4].

Approach

Figures 9a and 9b are dynamic plots of actual flow through the canister during unmanned testing. An RMV of 40 LPM (1.4 ACFM) was used in both tests as shown in Figures 9a (0 FSW) and 9b (305 FSW) (92.9 MSW).

The normal direction of system flow is from the exhalation bag through the canister and into the inhalation bag. Simultaneously, fresh gas is being injected through the sonic orifice and into the inhalation bag. During unmanned testing of the MK 11, it was observed that at specific times in the breathing cycle system flow direction reverses. This flow reversal is presented in Figures 9a and 9b as negative flow.

The duration of the CO_2 scrubber is directly proportional to the amount (mass) of CO_2 it absorbs. During reverse flow in this system the canister is being presented with CO_2-free gas; i.e., the gas in the inhalation bag consists of fresh make-up gas and gas previously scrubbed of CO_2. Using sine wave

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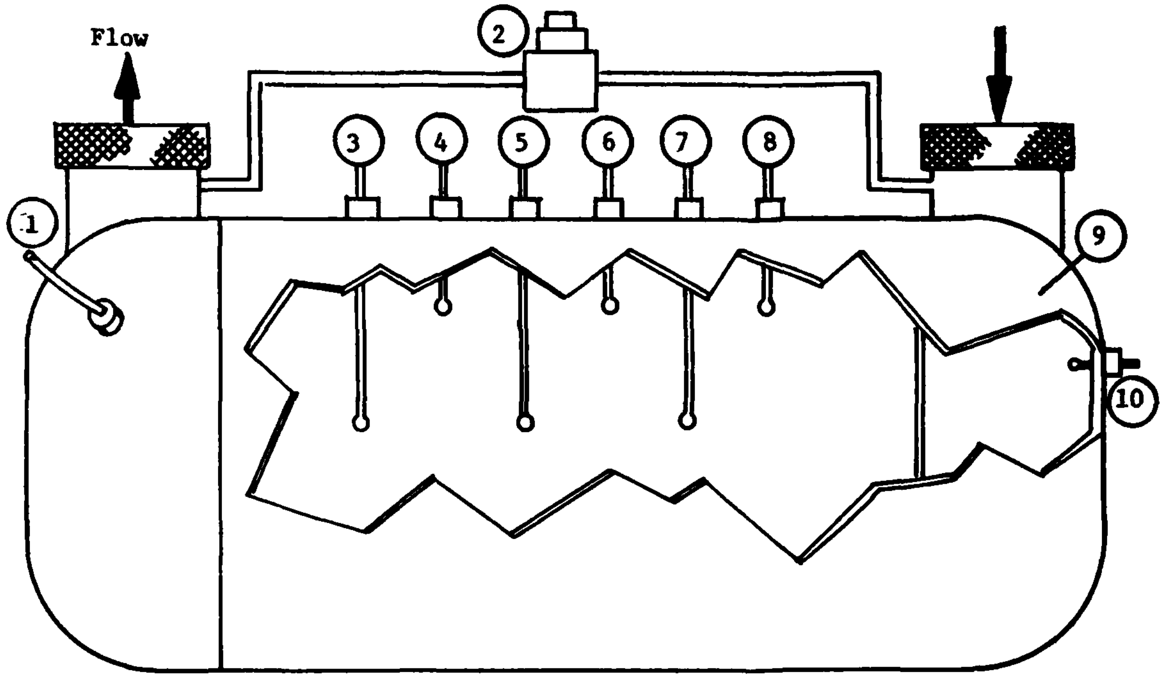
(2) Navy Experimental Diving Unit Report No. 18-78, *Life Support Characteristics of the MK 11 Semi-Closed Mixed Gas UBA at Intermediate Depths,* by C. A. Piantadosi and W. H. Spaur, November 1978.

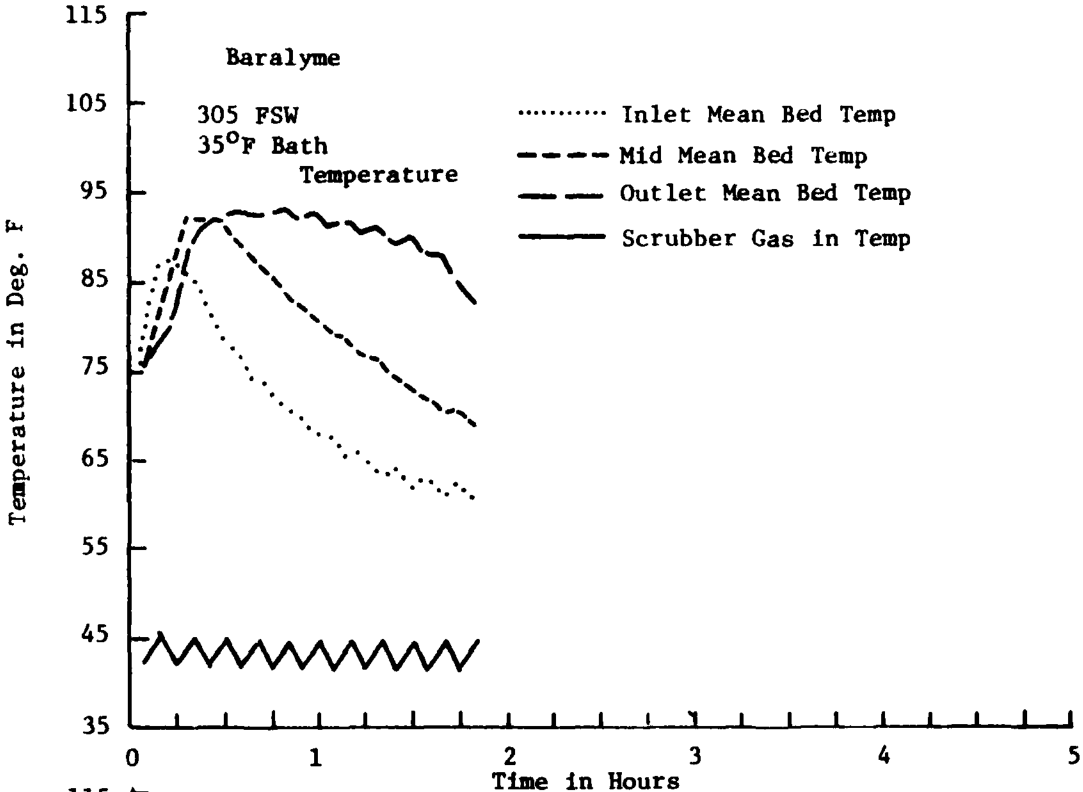
(3) Navy Experimental Diving Unit Report No. 10-78, *Evaluation of the MK 11, Mod-0 UBA in Cold Water,* by R. K. O'Bryan, R. L. Clinton, and R. A. Vendetto, May 1978.

(4) Hydrospace Laboratory Note 6-79, Index No. 71, *MK 11 Flow Test,* by G. W. Noble, April 1979.



1. CO_2 Sample Line
2. 0.5 PSID Transducer
3. Outlet-Center BED (YSI 701)
4. Outlet-Outer BED (YSI 701)
5. Mid-Center Outer BED (YSI 701)
6. Mid-Outer BED (YSI 701)
7. Inlet-Outer BED (YSI 701)
8. Inlet-Outer BED (YSI 701)
9. UBA MK 11 Canister
10. Scrubber Gas in Temp. (YSI 731)

FIGURE 4. SCRUBBER INSTRUMENTATION DIAGRAM



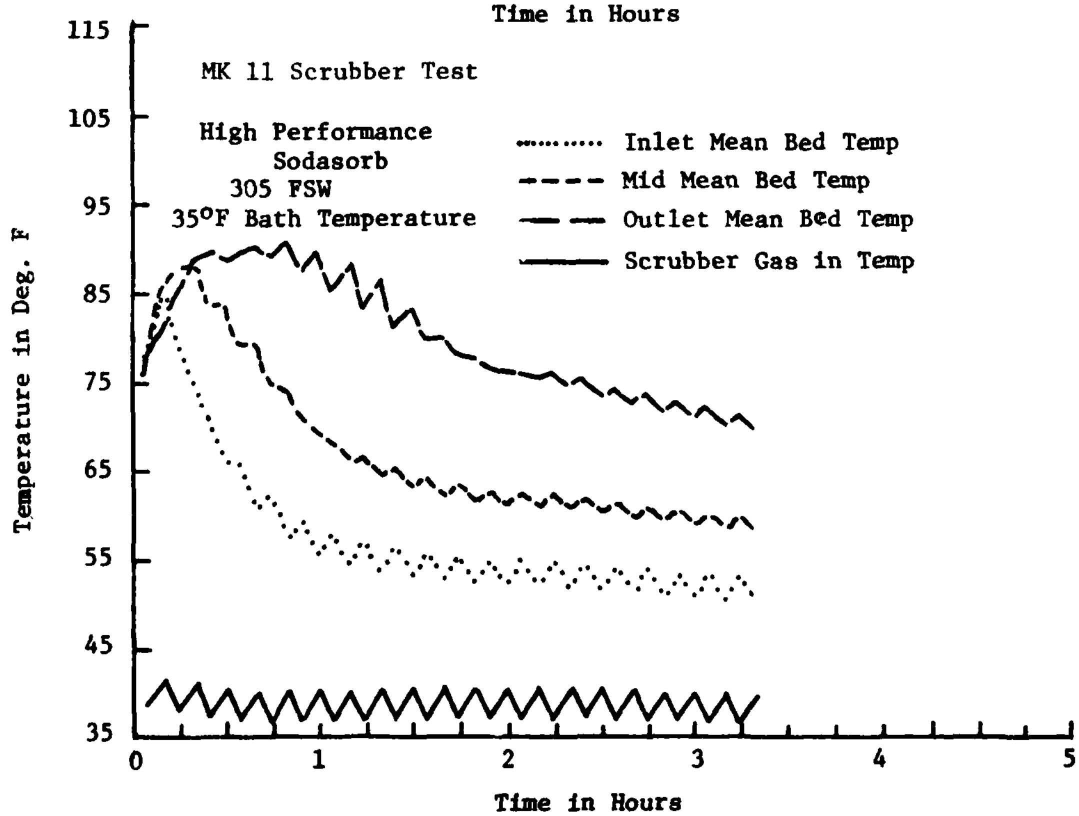
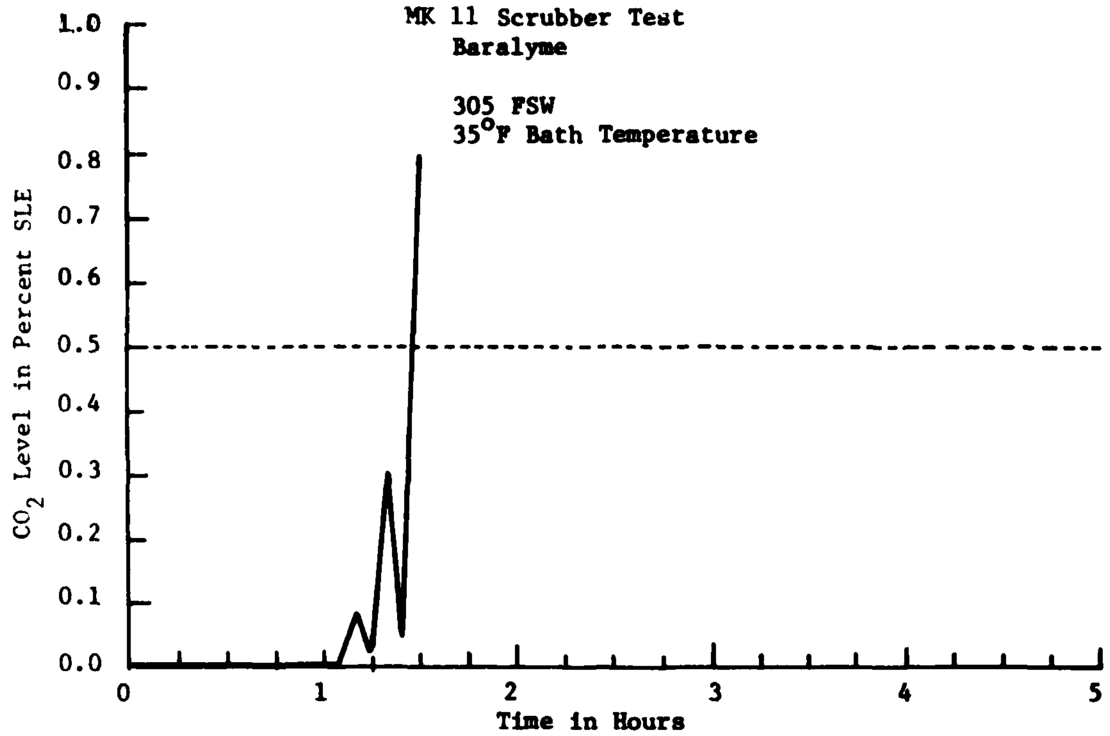


FIGURE 5. TYPICAL UNMANNED MK 11 CANISTER BED TEMPERATURES



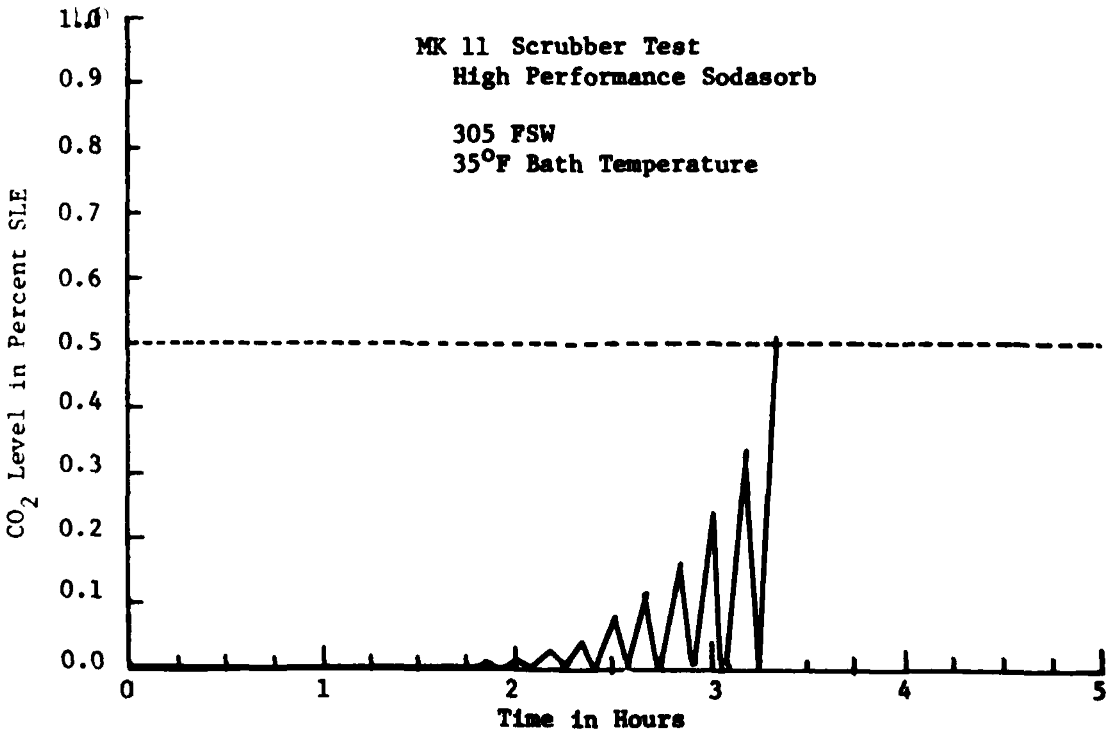
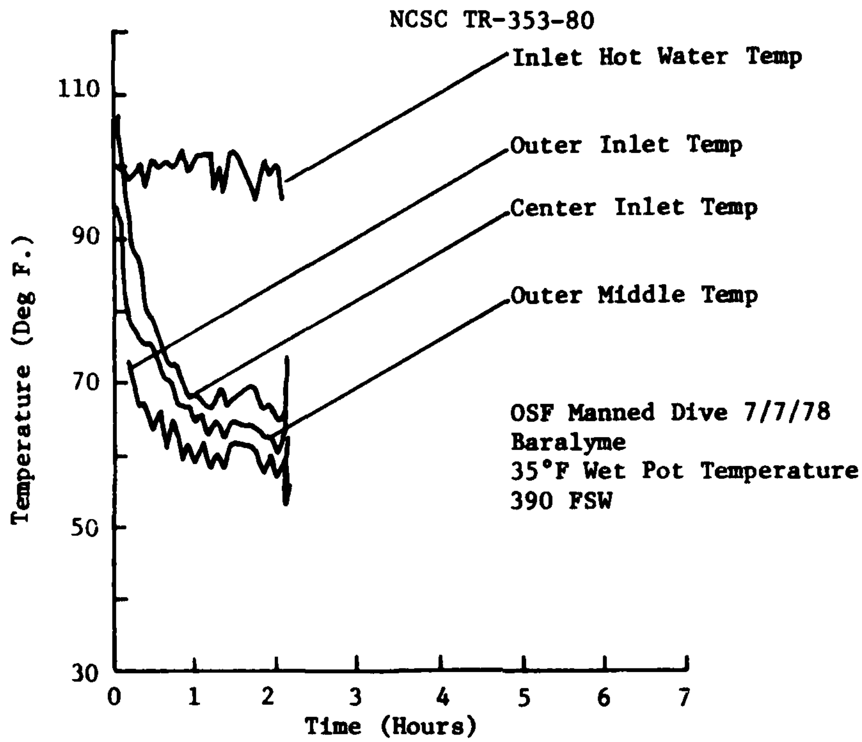


FIGURE 6. TYPICAL UNMANNED MK 11 CANISTER CO_2 SIGNATURES



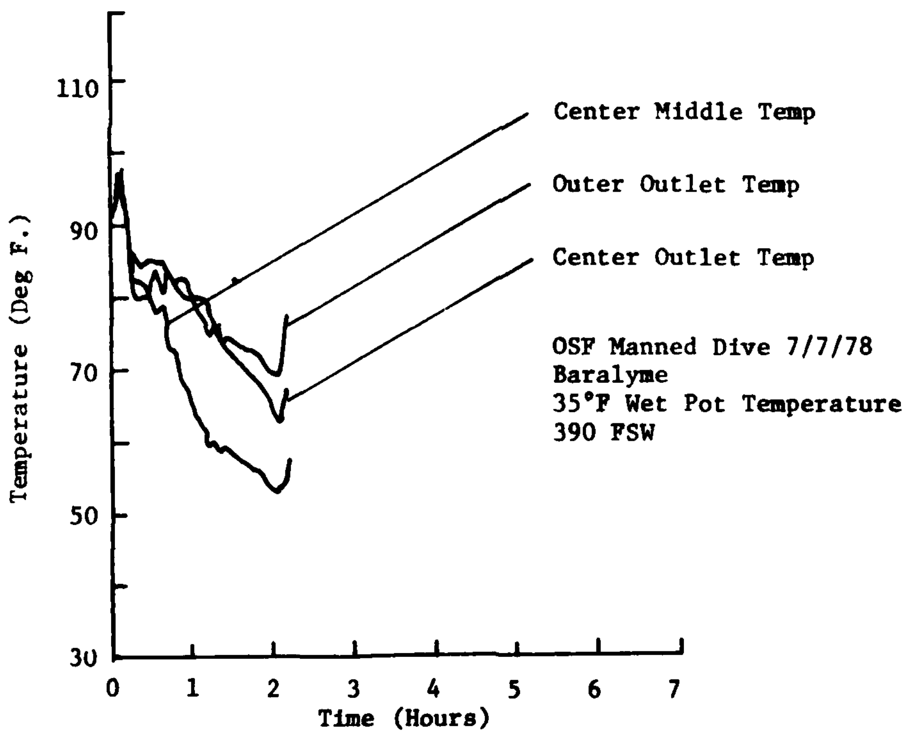


FIGURE 7. TYPICAL MANNED MK 11 CANISTER BED TEMPERATURES

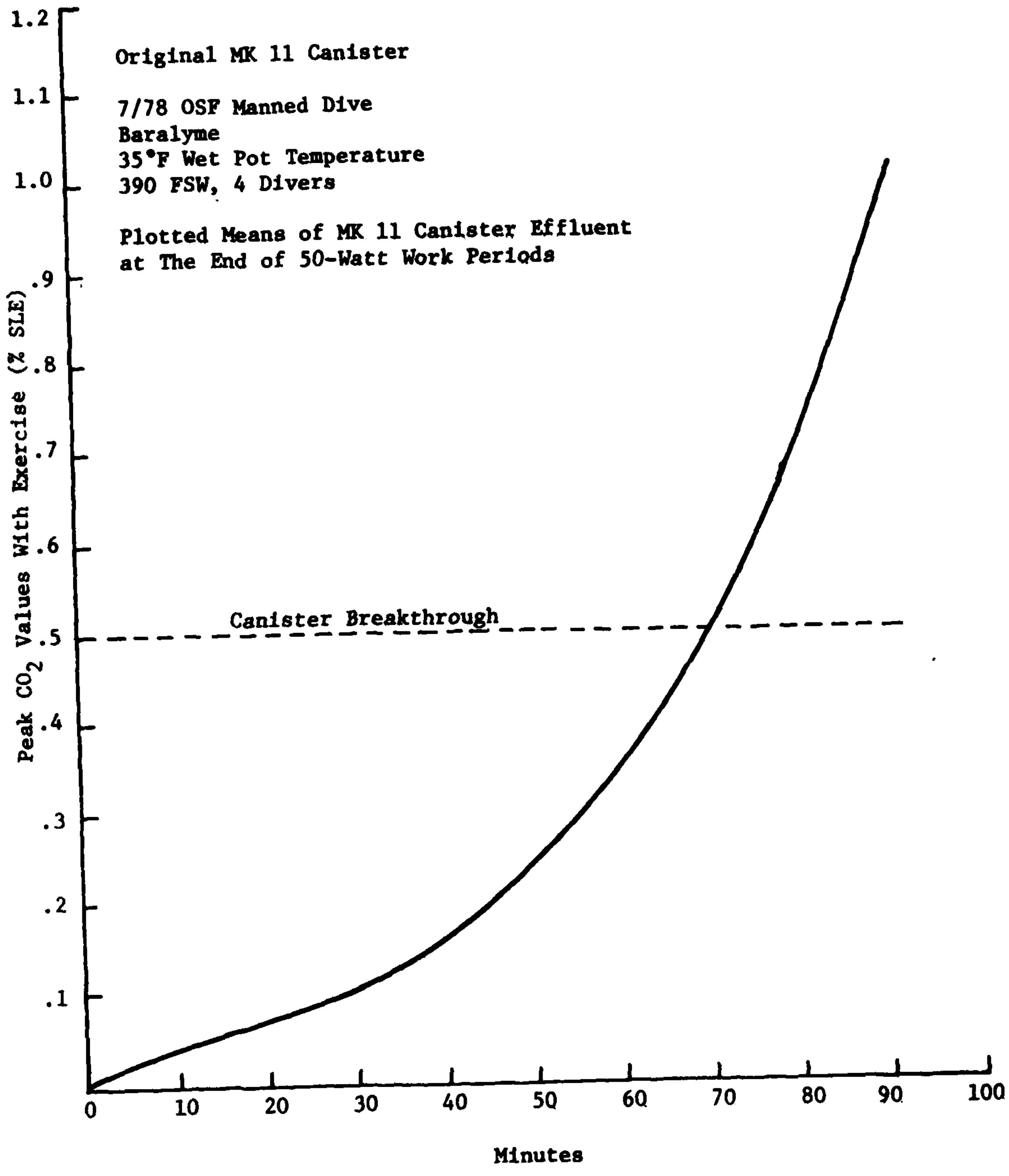


FIGURE 8a. MK 11 MANNED CO_2 SIGNATURE

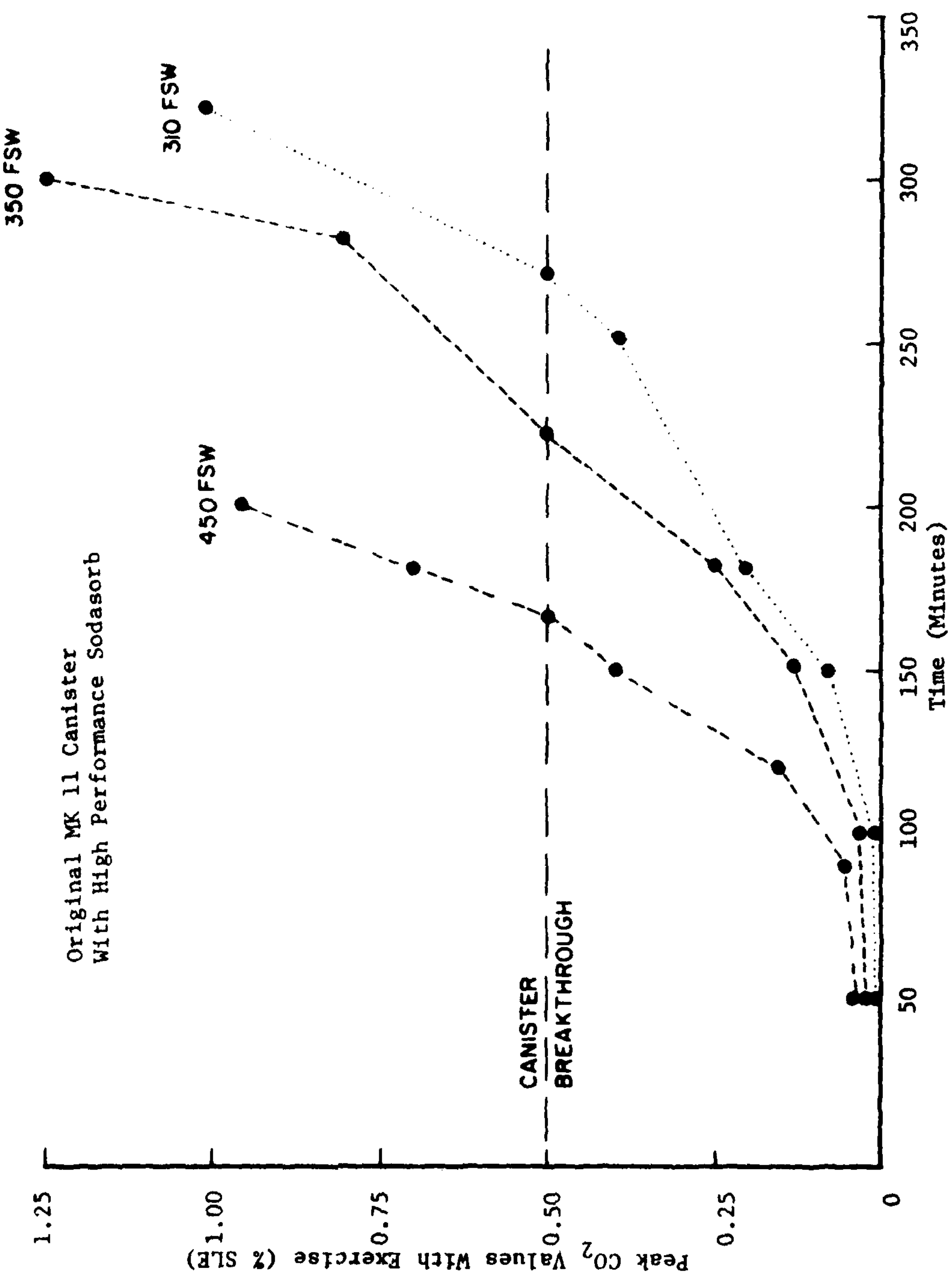


FIGURE 8b. MEAN CANISTER BREAKTHROUGH CURVES AT 310, 350, and 450 FSW, WITH 18 PERCENT HIGH PERFORMANCE SODASORB AT 35°F WET POT TEMPERATURE

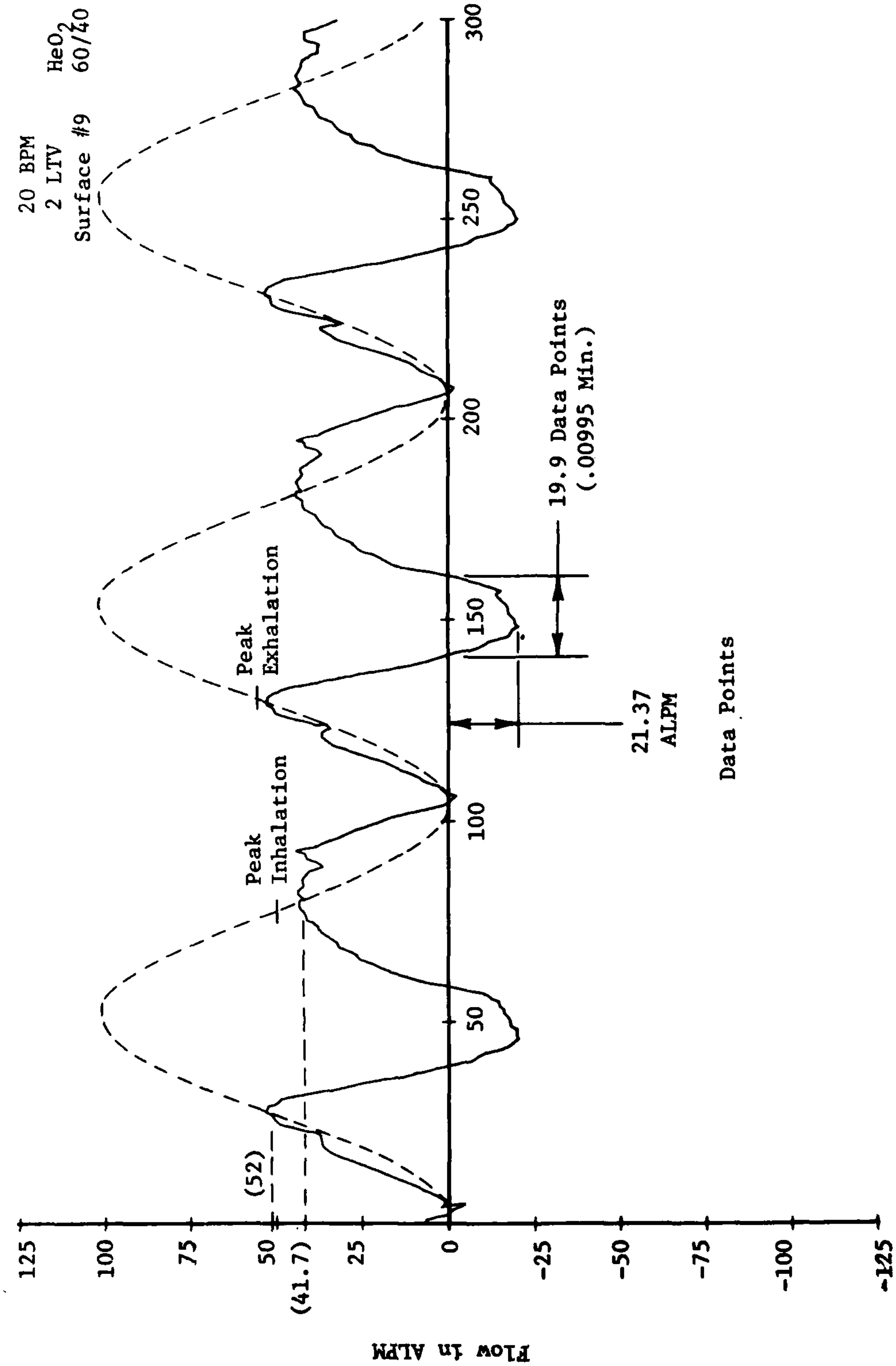


FIGURE 9a. MK 11 REVERSE FLOW TEST (1 ATA)

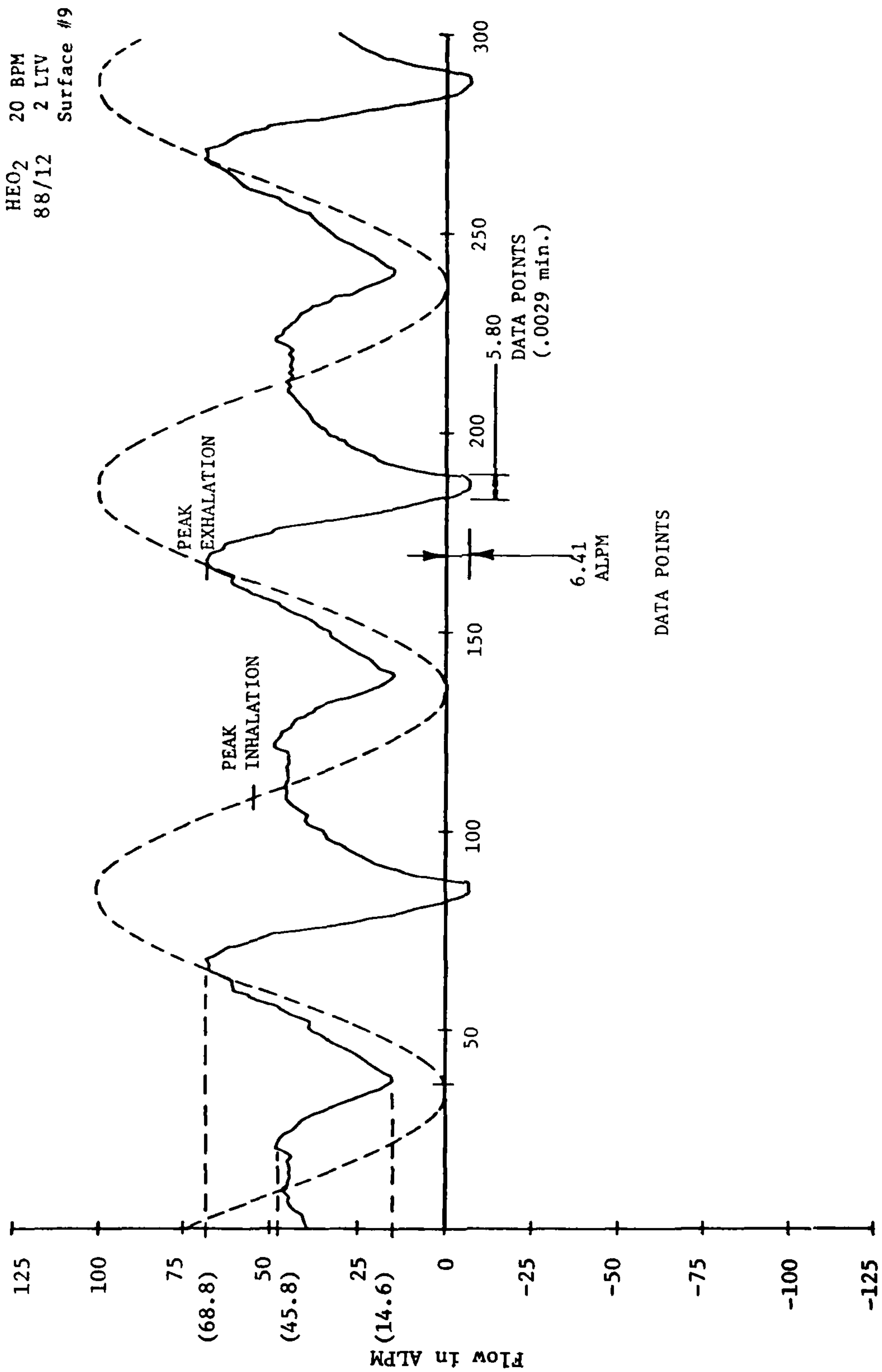


FIGURE 9b. MK 11 REVERSE FLOW TEST (305 FSW)

approximations for the curves recorded on Figures 9a and 9b permits a calculated estimate of actual flow in either direction through the canister per each breath. Comparing the calculated volume system flow through the canister and respective CO_2 level at 305 FSW (92.9 metres) with those at 1 ATA indicates that 55 percent more CO_2 is being presented to the scrubber at 305 FSW (92.9 MSW) than at 0 FSW (refer to Appendix A for calculations).

Results

As shown in the analysis of flow signatures (1 ATA, 40 RMV, and 305 FSW (93.0 MSW)), the MK 11 system has significant changes in system flow patterns to produce significant changes in quantities of CO_2 in the absorbent canister (Appendix A). Calculations indicate that approximately 55 percent more CO_2 flows into the canister at depth than at 1 ATA. This change in system flow is attributed to the minimum acceptable facility regulator setting being incompatible with present system sonic orifice selection. The minimum setting is a resultant of the constant absolute pressure (CAP) regulator minimum allowable setting. The flow reversal phenomenon is characteristic of the MK 11 at all tested breathing rates and depths.

Summation of total scrubber flow calculations (in both directions) indicates 1.02 actual litre/breath of gas is being dumped out the exhaust valve at 1 ATA and 0.14 actual litre/breath of gas is being exhausted at 305 FSW (93.0 MSW).

General Observations

Comparing Figures 10a and 10b reveals approximately the same ambient system flow at depth and surface; however, both the breathing signature and orifice flow reveal differences. The orifice flow is approximately 6.8 actual litres per minute (ALPM) at 50 FSW (15.2 MSW) and approximately 2.7 ALPM at 300 FSW (91.4 MSW) with the breathing signature showing a more positive pressure in the system at 50 FSW (15.2 MSW) than at 300 FSW (91.4 MSW). Table 1 shows the calculated flows (per the MK 11 Manual) for 50 FSW and 300 FSW, respectively, which compare favorably with the measured orifice flows of Figures 10a and 10b.

Figure 11 presents a dynamic plot of the pressure inside the exhalation bag at 50 FSW (15.2 MSW) and 300 FSW (91.4 MSW). The greater system positive pressure can be observed on the 50 FSW plot.

Conclusions

Based on the analysis of the system flow tests, it is apparent that the canister life is extended at depths of less than approximately 200 FSW (60.4 MSW) due to reductions in CO_2 presented to the canister. The reduction of CO_2 in the canister affleunt gas stream is a function of increased reverse flow which is the result of an incompatibility between the sonice orifice size in use and facility regulator setting available at shallow depths. This results in excessive flow of make-up gas at shallow depths.

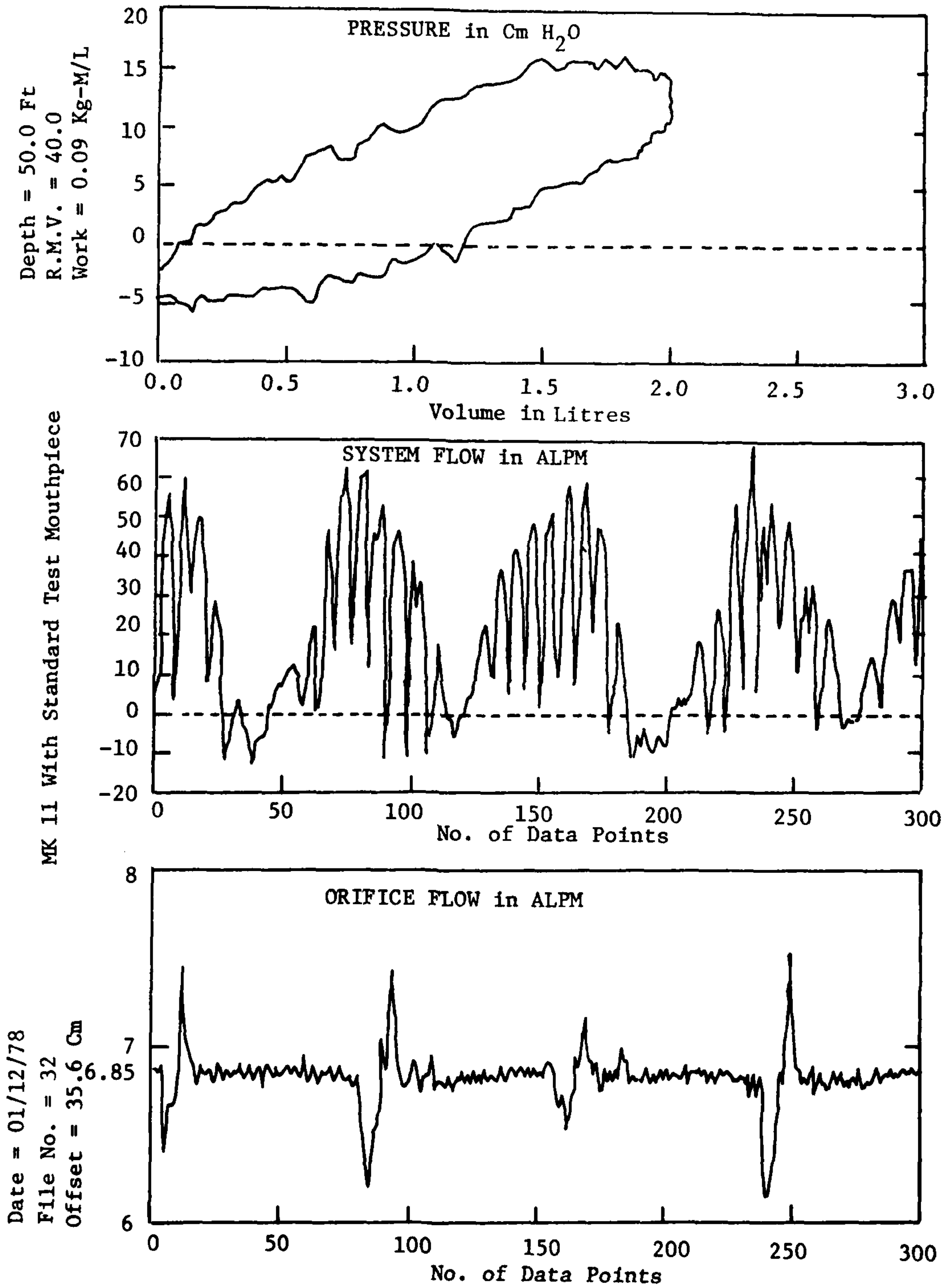


FIGURE 10a. MK 11 SYSTEM FLOW TESTS AT 50 FSW

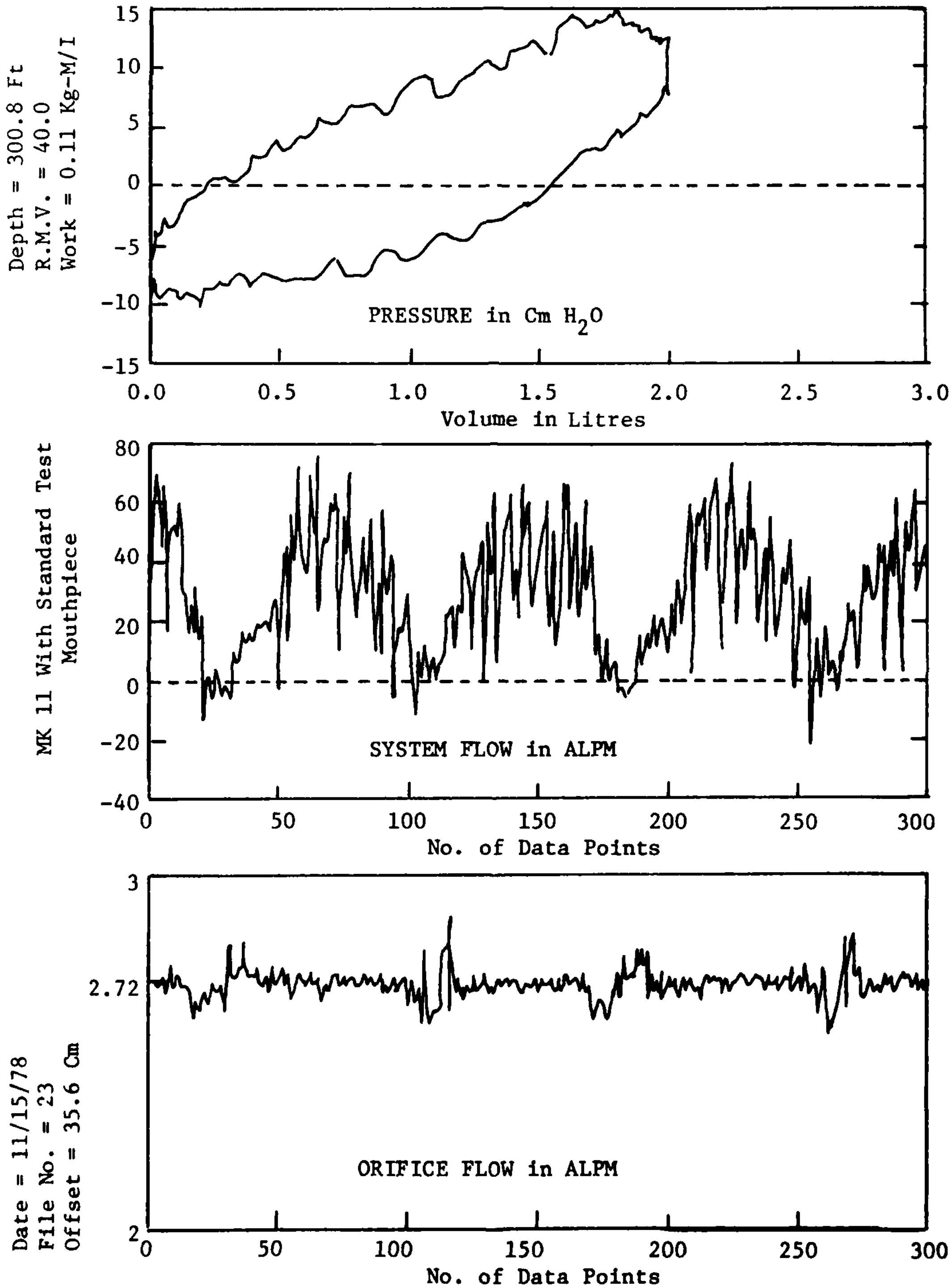


FIGURE 10b. MK 11 SYSTEM FLOW TESTS AT 300 FSW

TABLE 1

CALCULATED GAS FLOWS FOR 50 FSW AND 300 FSW

Emergency Bottle Pressure at 1 Atmosphere = 3000.0 psig
Emergency Bottle Temperature at 1 Atmosphere = 70.0°F
Water Temperature = 70.0°F

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50 FSW

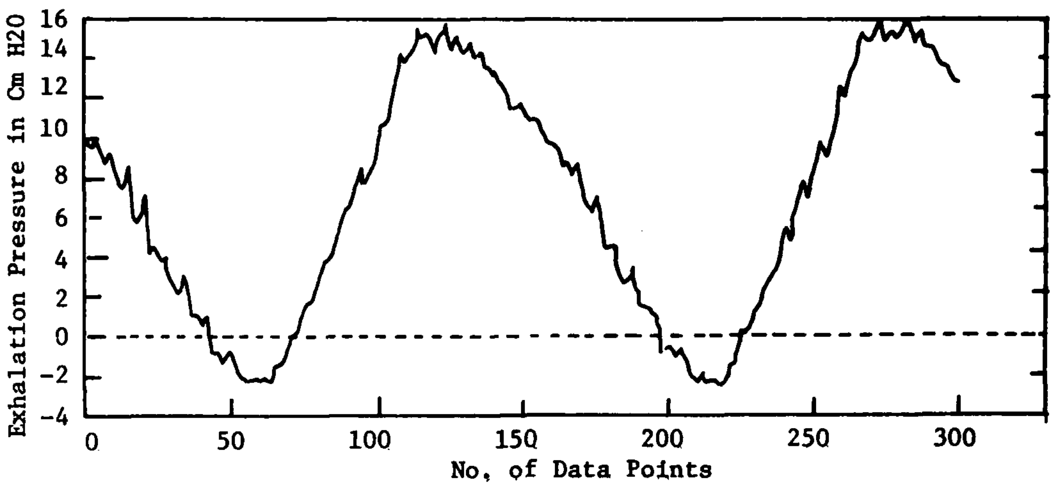
Oxygen Consumption Rate	1.60 (alpm)
Bag Level	0.1590
CAP Setting	265.00 (psia)
FR Setting	365.00 (psia)
Plug Gauge at Sat Depth (CAP)	213.33 (psia)
Plug Gauge at Sat Depth (FR)	313.33 (psia)

	Umbilical	Emergency
Oxygen Percent	40.00 (%)	40.00 (%)
Maximum Depth (O/C)	99.00 (ft)	132.00 (ft)
Minimum Depth (O/C)	0.00 (ft)	0.00 (ft)
Minimum Requirement Flow	5.58 (alpm)	5.58 (alpm)
Actual Gas Flow 6.36 (alpm)	16.00 (alpm)	11.62 (alpm)
B/L Minimum Depth PO_2	0.8384 (atma)	0.7650 (atm)
B/L Maximum Depth PO_2	0.8384 (atma)	0.7650 (atm)
Orifice Size	9.00	
Switchover Setting	2677.78 (psig)	

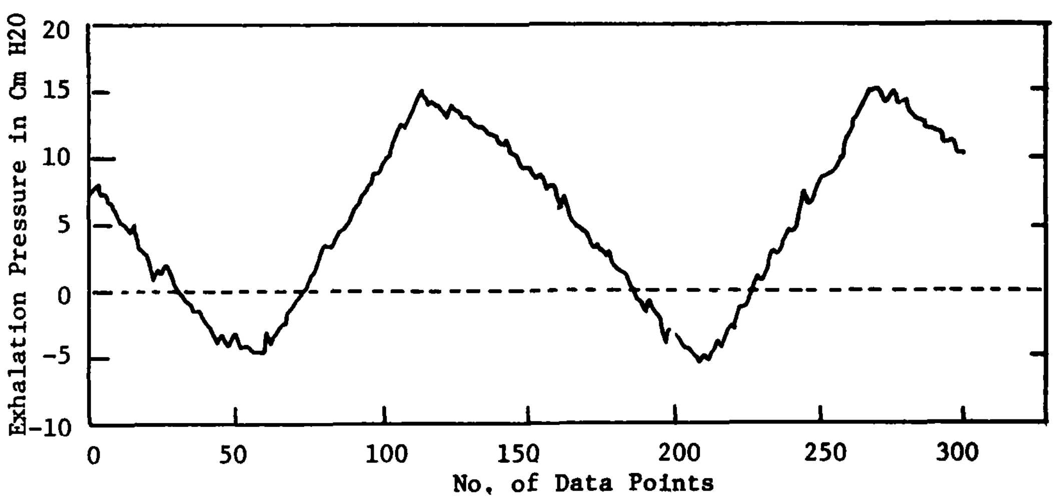
300 FSW

Oxygen Consumption Rate	1.60 (alpm)
Bag Level	0.0396
CAP Setting	340.00 (psia)
FR Setting	440.00 (psia)
Plug Gauge at Sat Depth (CAP)	176.96 (psia)
Plug Gauge at Sat Depth (FR)	276.96 (psia)

	Umbilical	Emergency
Oxygen Percent	15.00 (%)	19.00 (%)
Maximum Depth (O/C)	319.00 (ft)	314.37 (ft)
Minimum Depth (O/C)	55.00 (ft)	36.47 (ft)
Minimum Requirement Flow	13.92 (alpm)	10.22 (alpm)
Actual Gas Flow 2.63 (alpm)	26.54 (alpm)	19.20 (alpm)
B/L Minimum Depth PO_2	0.9633 (atma)	1.1741 (atm)
B/L Maximum Depth PO_2	0.9633 (atma)	1.1741 (atm)
Orifice Size	9.00	
Switchover Setting	2566.67 (psig)	



50 FSW, 40 RMV



300 FSW, 40 RMV

FIGURE 11. EXHALATION BAG PRESSURE AT 50 FSW AND 300 FSW

CANISTER MODIFICATIONS

Initial Modifications

Objective. Initially, a series of modifications were intended to identify the cause of the poor canister efficiency at depth and indicate an appropriate corrective design were tested[5].

Approach. The initial unmanned canister configurations tested at 650 FSW (198.1 MSW) are shown in Table 2. Attempts were made to adjust the wall surface area and gas velocity to maximize the time required to reach 0.5 percent SLE of carbon dioxide and minimize the work of breathing rate.

Results. Visual inspection of used canister beds led to the hypothesis that the gas was following the heated walls of the canister and not being distributed evenly across the absorbent bed. The results of Table 2, Canister Configuration II, Radial Flow Coaxial (Figure 2), indicate that during work cycles the higher respiratory rates and resultant higher gas velocities created better utilization of the absorbent bed in this configuration. The use of fins and additional wall surface appeared to improve the canister performance; however, the elongated bed increased the system work of breathing.

During the initial unmanned testing of the canister configurations, it was not known that a pressure drop greater than that of the original MK 11 canister could not be tolerated. Manned testing revealed that the MK 11 was already at the maximum tolerable work of breathing[6]. Figure 12 compares the breathing resistance of the MK 11 with other systems.

Alternative Modifications

Objective. Using the standard MK 11 canister shell, the objective was to produce a modified canister with greater efficiency and no additional breathing resistance. (At this point in the canister development, new non-return valves (Koegle) with less resistance than standard MK 11 non-return valves were adapted to fit the MK 11 facemask.)

Approach. Various internal changes to the MK 11 canister were attempted. Several heat exchanger modifications were tested. It was found that the optimum configuration for this depth and temperature range consisted of a 12-turn coil with a 2-inch outer diameter stainless steel sleeve and a hot water jacket. A production model of this design was fabricated and further testing was conducted with both the #9 and #13 sonic gas orifices. Configurations and results of alternative changes to the canister are shown in Table 3.

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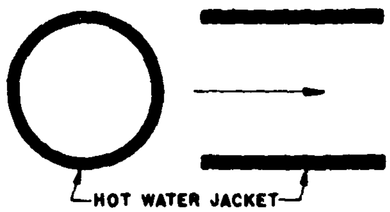
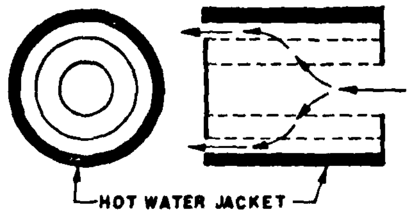
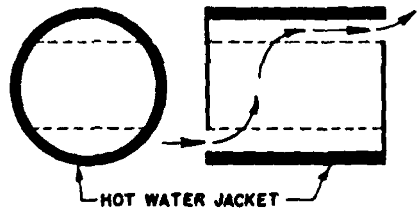
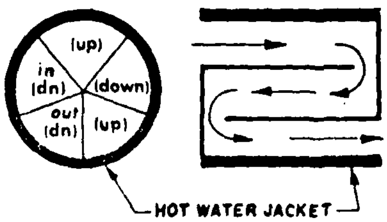
[5] Hydrospace Laboratory Note 3-79, Index No. 68, *MK 11 Scrubber Test, Sequence 3 at 650 FSW,* by G. W. Noble, April 1979.

[6] Navy Experimental Diving Unit Letter, *Manned Testing of the MK 11 UBA* at *650 FSW and 35°F (1.7°C),* Serial No. 62, dated 9 February 1979.

TABLE 2. INITIAL CANISTER CONFIGURATIONS TESTED UNMANNED[5]
(Sheet 1 of 3)

CANISTER CONFIGURATION	DESIGN FLOW PATH	REMARKS
I. BASELINE TEST-STANDARD CANISTER WITH HOT WATER JACKET (A) BATH AT 30° (4 TESTS) (B) BATH AT 35° (4 TESTS)		A - Bath at 30° B - Bath at 35°
II. RADIAL FLOW COAXIAL (A) PERFORATED METAL WALLS ON CENTRAL CORE (B) LINED INNER CORE WITH TWO LAYERS OF FILTER MATERIAL		Partially successful at forcing even flow distribution. Scrubbed better on work cycle.
III. VERTICAL FLOW (A) TWO LAYERS FILTER MAT'L-INLET, ONE LAYER-OUTLET (B) THREE LAYERS FILTER MATERIAL ON INLET, ONE LAYER ON OUTLET		Attempted to induce greater pressure drop to redistribute flow --- still unsatisfactory.
IV. SYMMETRIC SEGMENTS		Reduced wall area and increased gas velocity by 5X. Wall channeling appears to be the significant factor in the low flow situation.

[5]ibid.

TABLE 2. INITIAL CANISTER CONFIGURATIONS TESTED UNMANNED-CONTINUED

(Sheet 2 of 3)

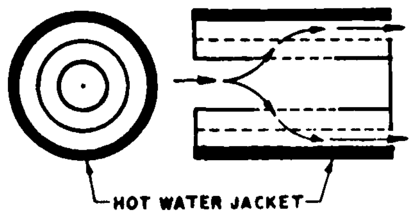
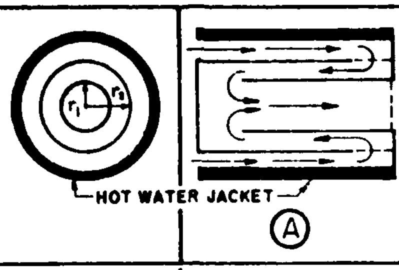
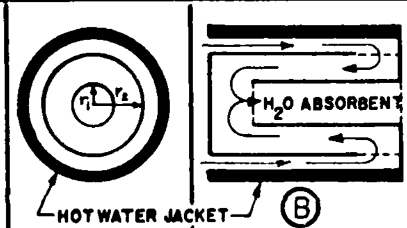
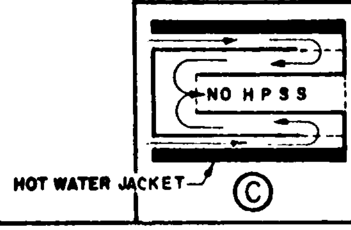
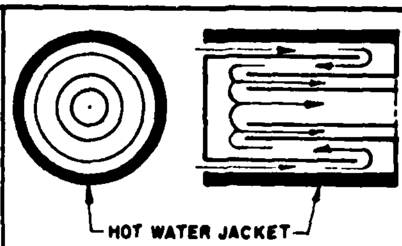
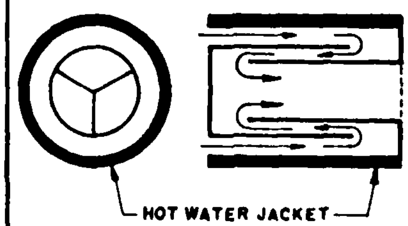
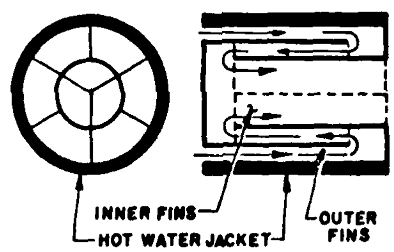
V. MODIFIED COAXIAL		Shortened perforated section of II to increase ΔP across bed.
VI. EXTENDED LENGTH COAXIAL (A) ALL PASSAGES FILLED WITH HPSS		Increased wall area & bed length and increased gas velocity. Work of breathing increased with time.
(B) SCREEN MOVED TO INLET OF CENTER SECTION AND CENTER FILLED W/H_2O ABSORBENT MATERIAL (INSTEAD OF HPSS)		Center section was wet on A. Test confirmed center of bed is being utilized in CO_2 absorption.
(C) DECREASED r_1 AND r_2 AND NO HPSS IN CENTER PASSAGE		Trying to keep ΔP at a minimum.

TABLE 2. INITIAL CONISTER CONFIGURATIONS TESTED UNMANNED-CONTINUED

(Sheet 3 of 3)

VII. EXTENDED LENGTH COAXIAL WITH EXTRA WALL AREA		No physical bridge between center 2 cylinders. More efficient particularly out of center sections. Performance same as before.
VIII. FINNED 3-PASS COAXIAL		Fins add more wall surface.
IX. DOUBLE FINNED THREE PASS COAXIAL		Fins improved both performance and work of breathing.

Results. The canister design combined with the new non-return valves produced a MK 11 diving system with acceptable canister life and decreased breathing resistance. Although it has not been confirmed, the canister has possibly increased diver inspired gas temperature by a few degrees.

Figure 13 depicts the modified instrumentation location for the heat exchanger canister design.

Figures 14a and 14b show canister temperatures and modified canister CO_2 level profiles for a typical unmanned duration test at 450 FSW (137.2 MSW) and 35°F (1.7°C) bath temperature. Manned testing of this canister configuration at 450 FSW (137.2 MSW) and 35°F (1.7°C) bath temperature resulted in a mean canister duration of 308 ($\pm$42) minutes and a breathing resistance lower than the original configuration.

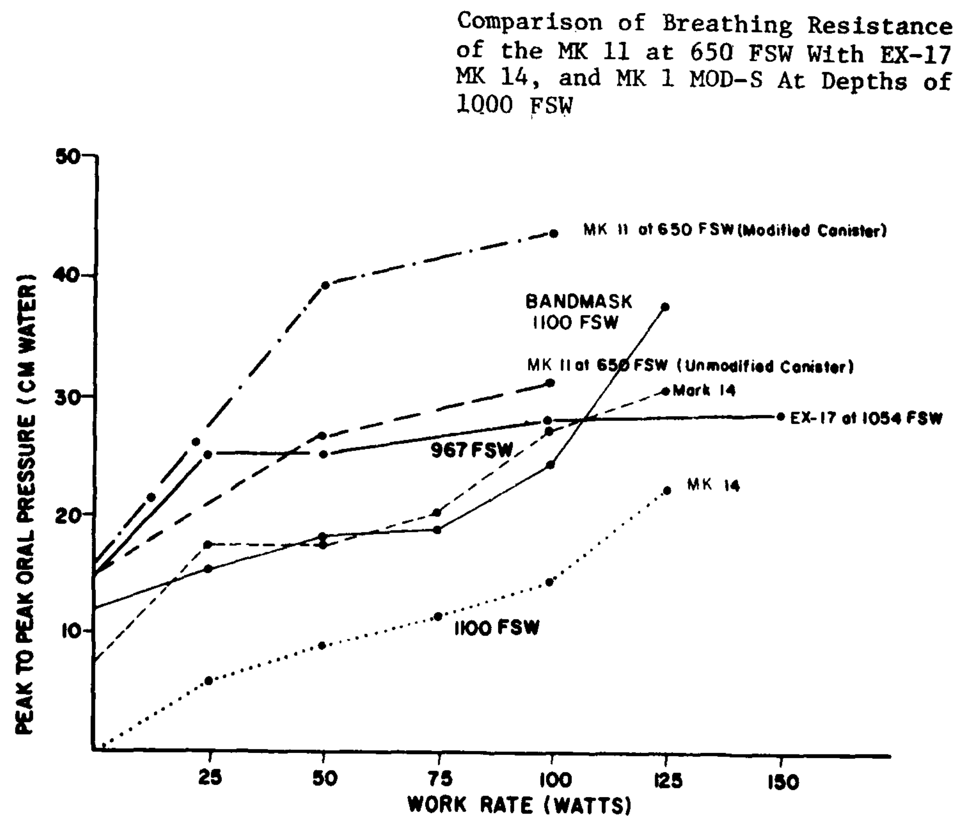
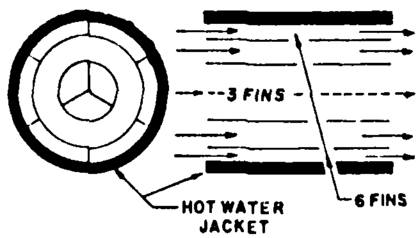
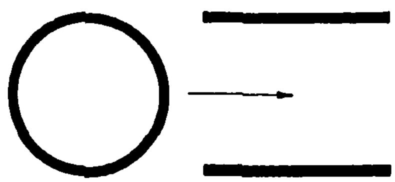
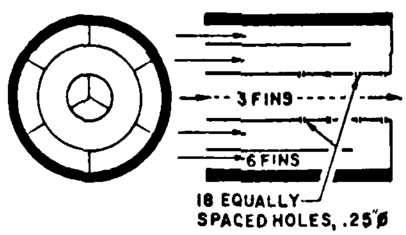
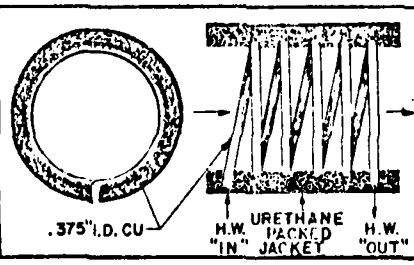


FIGURE 12. BREATHING RESISTANCE COMPARISONS

TABLE 3. RESULTS OF ALTERNATIVE CHANGES TO THE CANISTER[7]
(Sheet 1 of 3)

CANISTER CONFIGURATION	DESIGN FLOW PATH	REMARKS
I. OPEN BOTTOM ANNULAR (COAXIAL STRAIGHT THROUGH) TEST NO. 42		INCREASED WALL SURFACE AREA-MAINTAINING SAME LENGTH.
II. BASELINE STANDARD CANISTER TESTS NO. 43 & 44		STANDARD CANISTER WITH HOT WATER JACKET ONLY TO REESTABLISH BASELINE.
III. PORTED OPEN BOTTOM (MODIFIED STRAIGHT THROUGH) TESTS NO. 45 & 46		INCREASE WALL SURFACE AREA WHILE MAKING OUTER SEGMENT PATH LENGTH LONGER THAN CENTER. (INCREASE ΔP ON OUTER WALL TO DISTRIBUTE GAS INTO CENTER SECTION)
IV. INTERNAL HEAT EXCHANGER WITH WATER JACKET COIL TEST 47: HPSS TEST 49: BARALYME AT 450 FSW AND 30°F BATH.		EXPLORED EFFECTS OF DIRECT HEATING

[7]Hydrospace Laboratory Note 4-79

TABLE 3. RESULTS OF ALTERNATIVE CHANGES TO THE CANISTER
(Sheet 2 of 3)

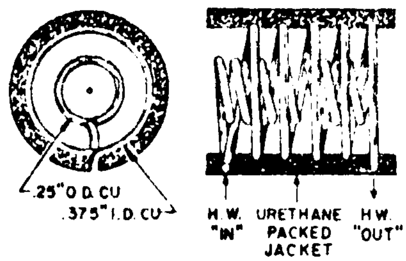
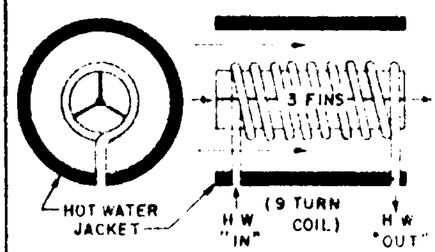
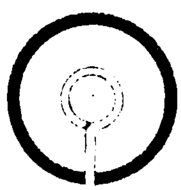
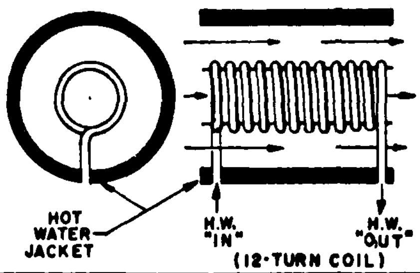
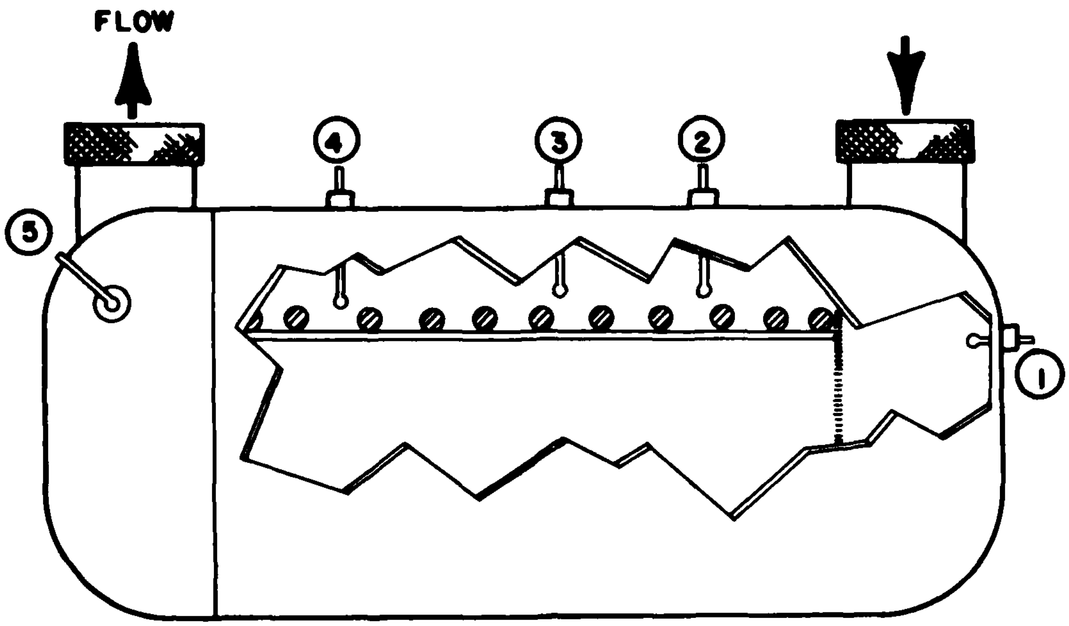
CANISTER CONFIGURATION	DESIGN FLOW PATH	REMARKS
V. SIMULATE BAGGEY TEST NO. 48	SAME AS II	RAISED BATH TEMP. TO 50°F TO SIMULATE HEATED BAGOVER SYSTEM
VI. DOUBLE INTERNAL HEAT EXCHANGER TESTS NO. 50, NO. 51 & NO. 59		FREE STANDING INNER COIL → BED FLOODED ATTEMPTED TO UTILIZE CENTER OF CANISTER THROUGH HEATING
VII. CENTER HEAT EXCHANGER TEST: NO. 52 HOT WATER T=110° NO. 53 HOT WATER T=117° NO. 54 HOT WATER T=103° NO. 55 HOT WATER T=110° AND USED MK. II MASK		3" O.D. ALUMINUM SLEEVE TO DETERMINE EFFECTS OF ADDITIONAL HEATED WALL
VIII. MODIFIED CENTER HEAT EXCHANGER TEST: NO. 56 SAME AS TEST NO. 55 EXCEPT NO FINS (3" AL INNER SLEEVE ONLY.)	 SAME AS VII EXCEPT NO FINS	SIMPLIFIED ASSEMBLY OF HEATED WALL BY REMOVING CENTER FINS.

TABLE 3. RESULTS OF INTERNAL CHANGES TO THE CANISTER
(Sheet 3 of 3)

CANISTER CONFIGURATION	DESIGN FLOW PATH	REMARKS
IX. 12 TURN COIL WITH 2" O.D. STAINLESS STL. SLEEVE TESTS NO. 57 AND 58		2" O.D. STAINLESS STL. SLEEVE OPTIMIZE BED TEMPERATURES
X. 12 TURN COIL WITH 2½" O.D. STAINLESS STL. SLEEVE	SAME AS IX EXCEPT WITH 2½" O.D. SLEEVE TEST NO. 60, WITHOUT HOT WATER ORIFICE TEST NO. 61, WITH HOT WATER ORIFICE	ATTEMPTED TO FORCE EVEN HEAT DISTRIBUTION THROUGHOUT THE CANISTER



LEGEND

1. Scrubber Gas Inlet Temperature
2. Canister Inlet Temperature
3. Canister Center Temperature
4. Canister Outlet Temperature
5. CO_2 Sample Line

FIGURE 13. MODIFIED MK 11 CANISTER HEAT EXCHANGER INSTRUMENTATION

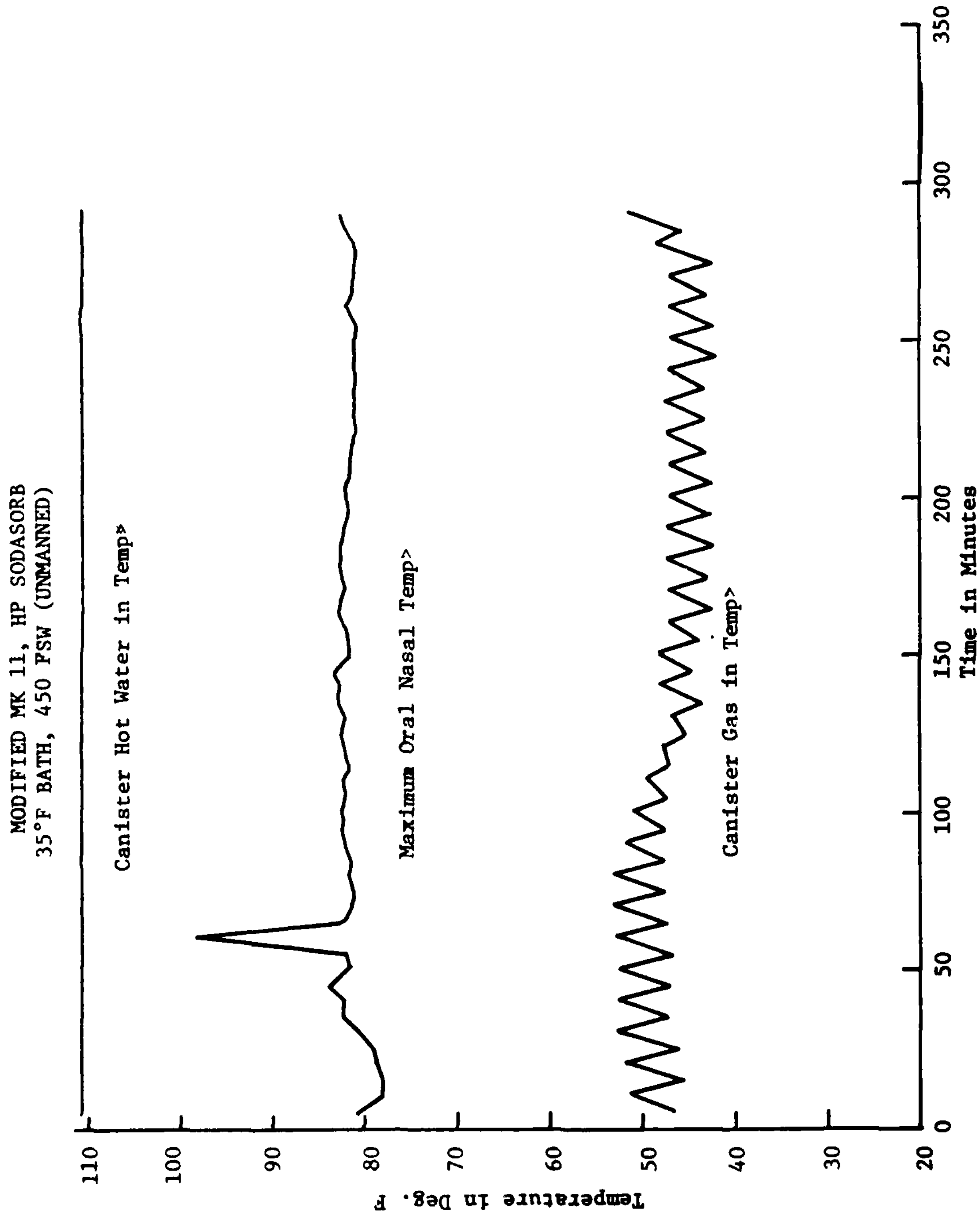


FIGURE 14a. TYPICAL UNMANNED CANISTER DURATION TEMPERATURES

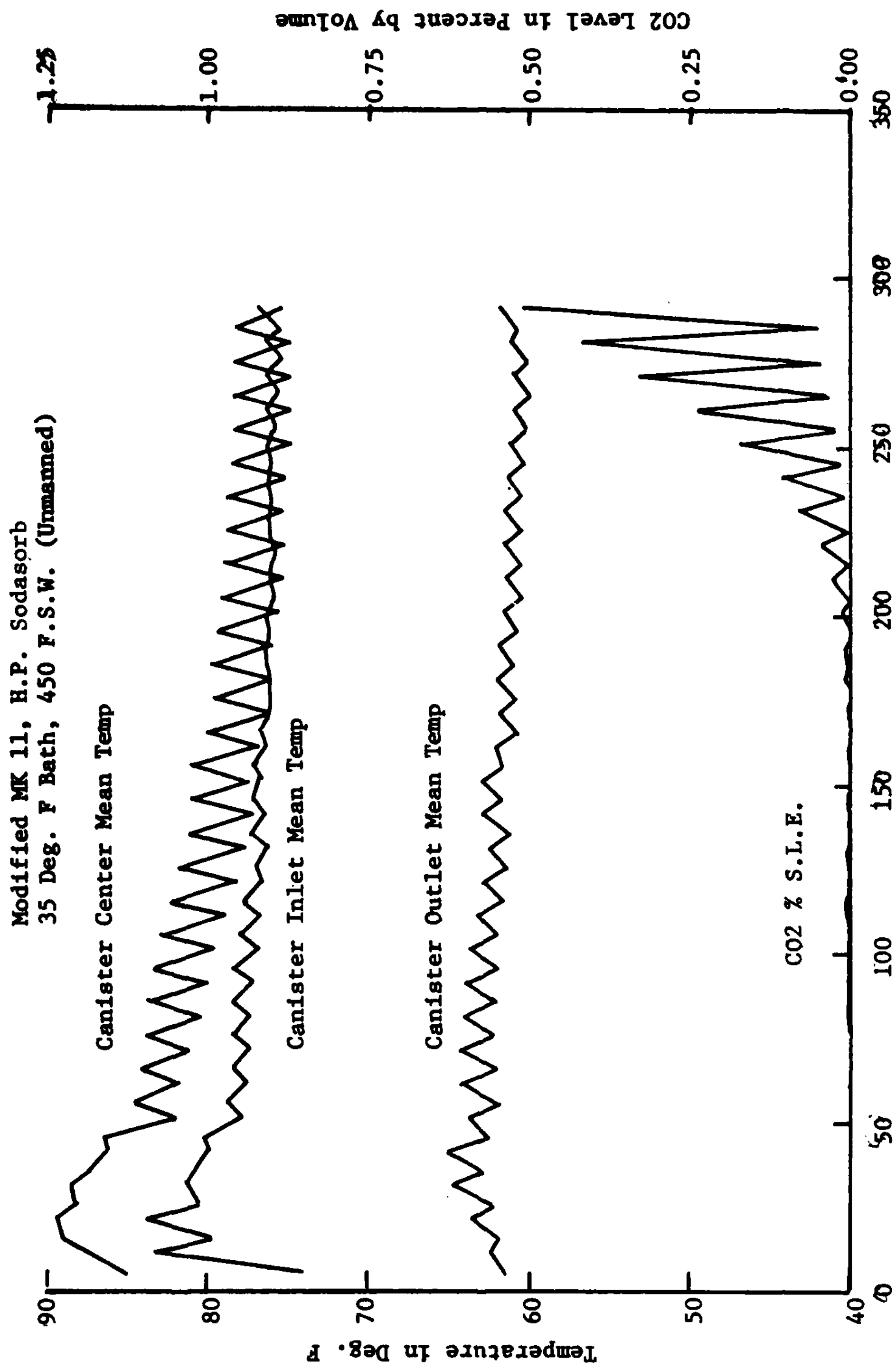


FIGURE 14b. TYPICAL UNMANNED MODIFIED CANISTER DURATION CO_2 LEVEL PROFILES

MK 12 CO_2 SCRUBBER DEVELOPMENT

MK 12 MIXED-GAS RECIRCULATOR SYSTEM DESCRIPTION

The MK 12 Surface Supported Diving System (SSDS) mixed-gas mode (Figure 15) was designed and developed to serve as the United States Navy's basic tethered system for use in nonsaturated mixed-gas diving operations. The U.S. Navy conducted a commercial diving equipment survey in 1971; development of the MK 12 began in 1972 to satisfy SOR 46-54 requirements. The mixed-gas recirculator was under development at NCSC from November 1976 to October 1978 and successfully completed technical evaluation (TECHEVAL) in December 1978.

Recirculator Assembly

Four operating configurations are available with the MK 12 mixed-gas recirculator. In order of preferred use, they are: umbilical supply, semi-closed circuit; umbilical supply, open circuit; emergency supply, semi-closed circuit; and emergency supply, open circuit. Figures 16 and 17 depict the MK 12 recirculator assembly.

During normal (umbilical, semi-closed) operations, surface supplied gas enters the recirculator low-pressure manifold and passes through the ejector nozzle. As this gas passes through the ejector throat, it creates a venturi effect which draws the gas to be recirculated through the canister where it is scrubbed of carbon dioxide. This mixture of surface supplied and scrubbed gas enters the helmet through the supply (inlet) hose and mixed-gas, one-way valve. While approximately 10 percent of the gas in the helmet is exhausted through the adjustable exhaust valve, 90 percent is pulled into the canister via the return (outlet) hose to complete the recirculation circuit.

Umbilical supply, open circuit, is used in the event of a recirculator failure when surface supplied gas can be fed directly to the helmet, bypassing the recirculator. This configuration is also used when ventilating the diver on O_2.

Two mixed-gas emergency configurations use the emergency bottle located in the recirculator. Emergency, semi-closed circuit, is utilized when surface supplied gas is lost or becomes contaminated and the recirculator remains operational. Emergency, open circuit, is used if the surface supplied gas is lost and the recirculator fails. High pressure mixed gas from the emergency bottle is regulated at 30 pounds per square inch gauge (psig) overbottom pressure and is fed through a bypass whip to the helmet.

FIGURE 15. MK 12 MIXED-GAS CONFIGURATION

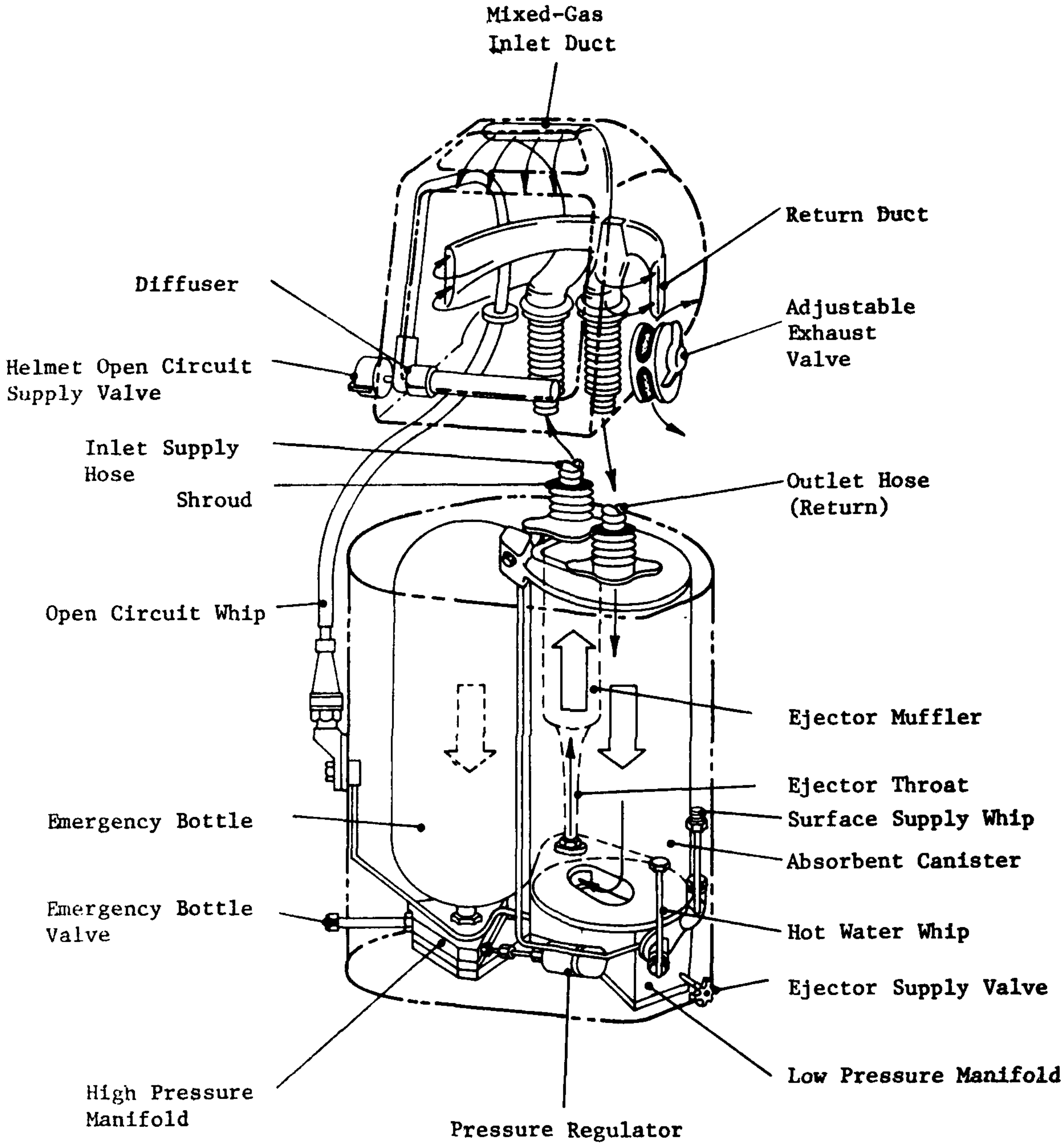


FIGURE 16. RECIRCULATOR ASSEMBLY/HELMET FLOW (SEMI-CLOSED MODE)

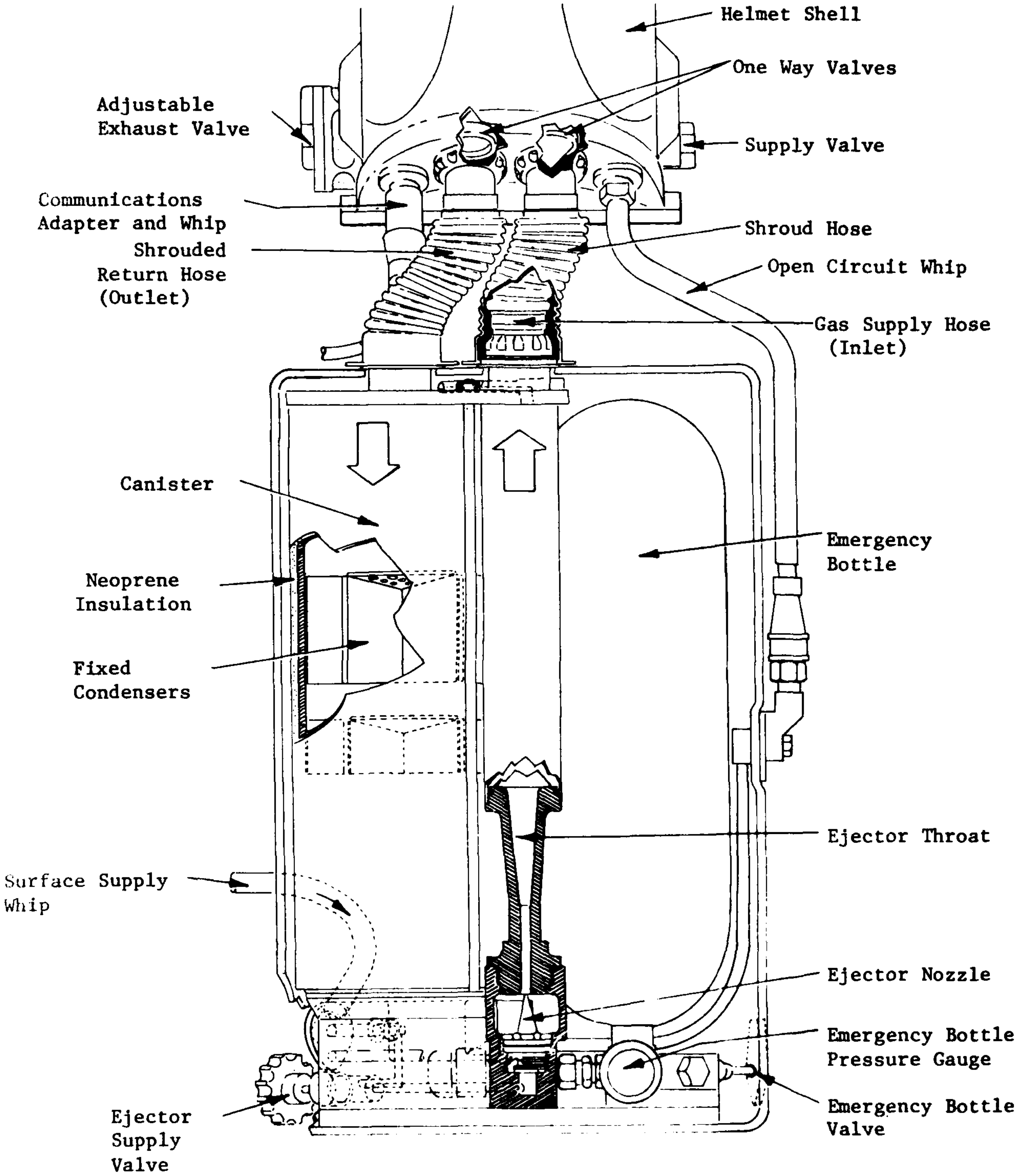


FIGURE 17. RECIRCULATOR ASSEMBLY WITH HELMET INTERFACE (REAR VIEW)

DEVELOPMENTAL TESTING

Total System and Component Pressure Drops

The purpose of this test series was to identify and minimize the system/ component pressure drops[8]. The most significant results of these tests were: a) the utilization of conical design (Koegle) non-return valves in lieu of more commonly used "Mushroom-Flapper" non-return valves (Figure 18 illustrates the reduction in system resistance due to these valves); and b) breathing hoses were optimized with an 1½-inch inside diameter (ID).

Ejector Development

The purpose of this test series was to develop an ejector assembly that will supply a recirculator system flow of 6 actual cubic feet per minute (ACFM) (170 litres/per min (ALPM)) against the MK 12 optimized total system losses with a nozzle flow of 0.4 to 0.5 acfm (11.3 to 14.2 ALPM) (at the diver depth) at a maximum ejector supply pressure of 135 pounds per square inch (9.49 kg per square cm) differential (psid) overbottom pressure[9] [10].

Figure 19 shows the ejector configuration identification method for the MK 12 system. Table 4 lists the performance characteristics of some of the ejectors tested. Empirical testing culminated in an ejector for MK 12 application which met all design requirements. Figure 20 shows performance characteristics of the final MK 12 design.

MK 12 Scrubber Development

Background. During manned and unmanned testing of an early scrubber prototype in the period of December 1976 to January 1977, it was determined that the duration of effective CO_2 scrubbing was not adequate[11][12][13].

Diagnostic Test Objective. In an early attempt to better understand the operating phenomena of this CO_2 scrubber, a series of diagnostic tests were conducted.

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[8] Hydrospace Laboratory Note 1-77, Index No. 14, *Mk 12 SSDS Mixed-Gas Mode and Total System and Component Pressure Drop Test,* by G. W. Noble, May 1977.

[9] Hydrospace Laboratory Note 2-77, Index No. 15, *MK 12 SSDS Ejector Development Test,* by G. W. Noble, February 1977.

[10] Hydrospace Laboratory Note 3-77, Index No. 16, *Recirculator System flow Test (Smooth Bore Nozzle),* by G. W. Noble, February 1977.

[11] Hydrospace Laboratory Note 13-76, Index No. 13, *Recirculator Duration Test,* by G. W. Noble, June 1976.

[12] Hydrospace Laboratory Note 23-77, Index No. 34, *MK 12 SSDS Recirculator Canister Test,* by G. W. Noble, August 1977.

[13] Navy Experimental Diving Unit Report No. 10-77, *Manned Evaluation of the Prototype MK 12 SSDS Helium-Oxygen Mode,* by R. K. O'Bryan, September 1977.

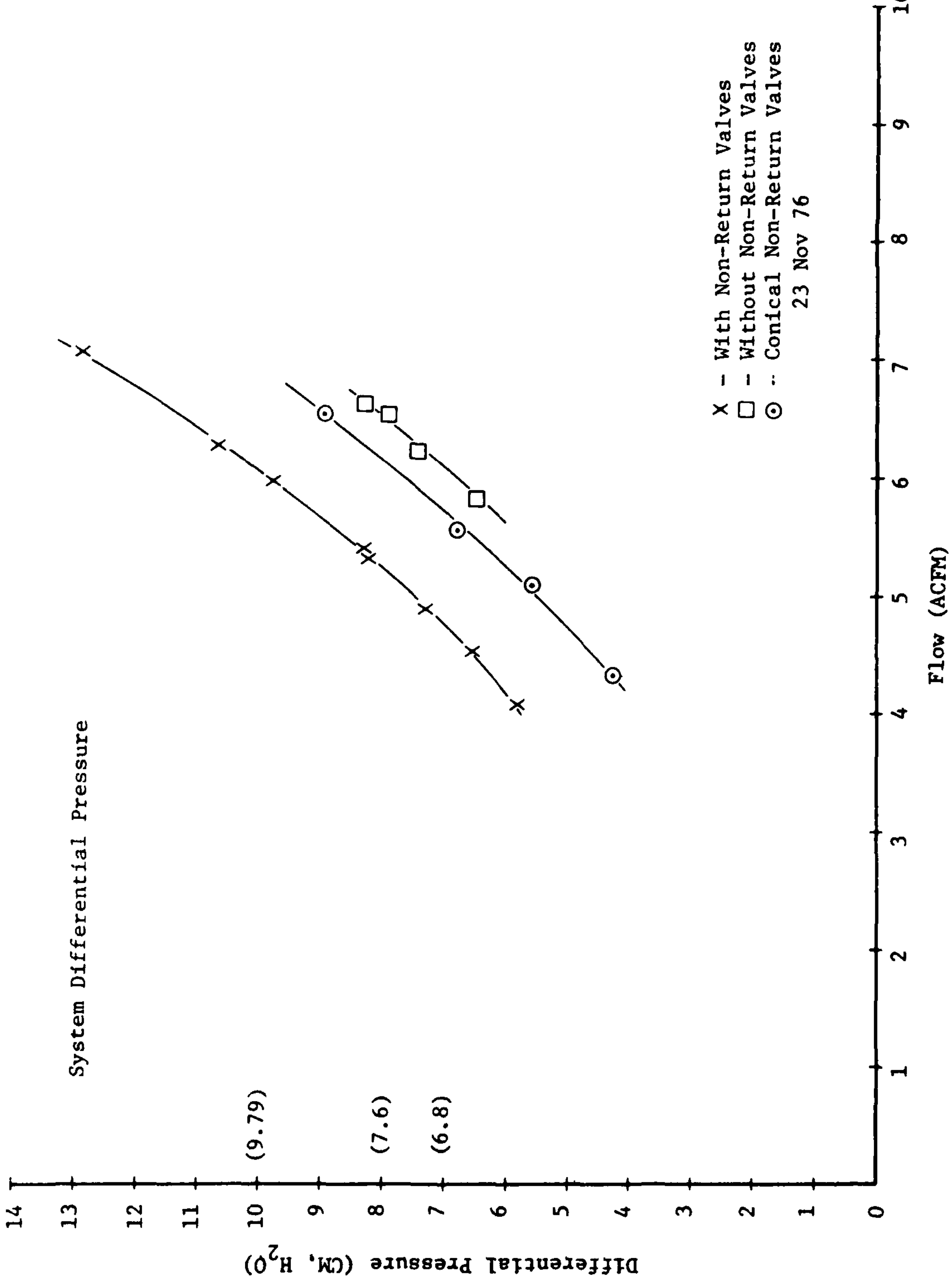
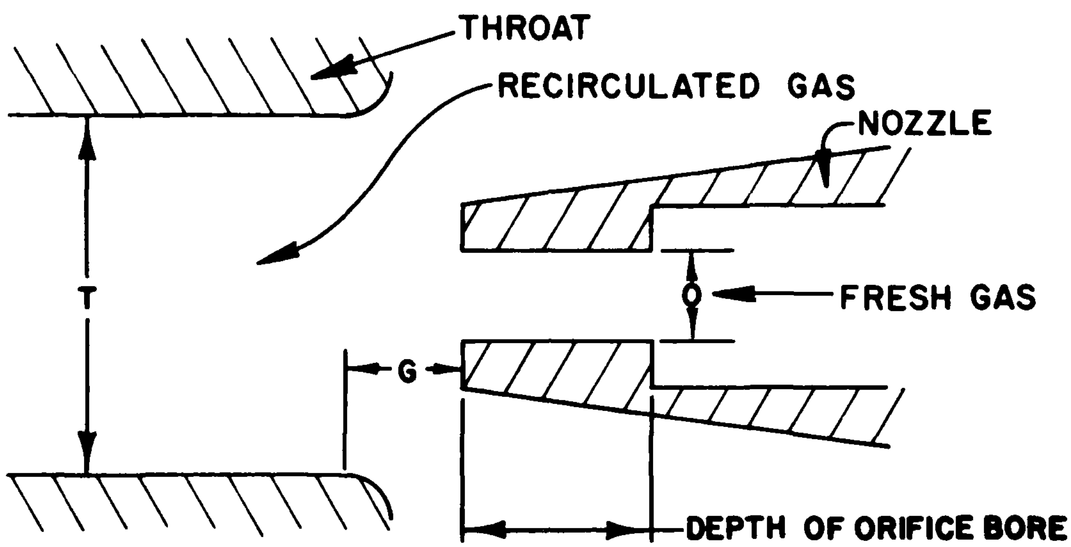


FIGURE 18. MK 12 SYSTEM DIFFERENTIAL PRESSURE (KOEGLE VALVES)



Legend:

0 - Orifice
0.028 - Diameter of Orifice Opening
TT - Nozzle Configuration (Smooth Internal and External Taper)
22 - Depth of Orifice Bore (Thousandths of an Inch)
T - Throat
ST - Short Throat
0.312 - Diameter of Ejector Throat Staright Section (Inches)
F - 25 Milcron Filter Assembly Installed

Example: 0 =0.28TT22/T = ST.312FC/G = 0.156

FIGURE 19. EJECTOR CONFIGURATION IDENTIFICATION

TABLE 4

SELECTED EJECTOR TEST DATA*

(Sheet 1 of 2)

EJECTOR TYPE	NOZZLE PRESSURE (PSID)	NOZZLE FLOW (ACFM)	EJECTOR FLOW (ACFM)	SYSTEM ΔP (in H_2O)	DEPTH (FSW)	GAS		EFFICIENCY
						MIX	% BY VOLUME	RATIO
Original G.E. 0=.025/T=.40/G=.20	60.2	0.62	5.96	-	380	HeO_2	84/16	9.63
	59.4	0.61	5.02	-	380	HeO_2	84/16	8.29
	75.7	0.82	5.15	-	380	HeO_2	84/16	6.29
	76.3	0.83	5.10	-	380	HeO_2	84/16	6.13
	102.1	1.02	6.00	-	380	HeO_2	84/16	5.90
	102.4	1.02	5.98	-	380	HeO_2	84/16	5.85
	134.6	1.22	6.98	-	380	HeO_2	84/16	5.71
	135.0	1.23	6.89	-	380	HeO_2	84/16	5.61
G.E. (MODIFIED) 0=.035/T=.312/G=.156	60.80	0.49	4.88	7.24	380	HeO_2	84/16	10.01
	80.65	0.56	5.57	8.77	380	HeO_2	84/16	8.77
	100.65	0.63	6.28	10.58	380	HeO_2	84/16	9.98
	135.40	0.74	7.31	13.49	380	HeO_2	84/16	9.86
G.E. (MODIFIED) 0=.035/T=.312L/G=.156 (LONG THROAT)	61.05	0.48	5.07	7.51	380	HeO_2	84/16	10.46
	80.55	0.56	5.93	9.59	380	HeO_2	84/16	10.67
	101.65	0.63	6.68	11.54	380	HeO_2	84/16	10.63
	134.95	0.74	7.67	14.32	380	HeO_2	84/16	10.41
	60.90	0.46	4.87	7.68	450	HeO_2	84/16	10.63
	82.00	0.53	5.70	9.91	450	HeO_2	84/16	10.71
	100.35	0.59	6.38	11.85	450	HeO_2	84/16	10.73
	137.00	0.70	7.45	14.77	450	HeO_2	84/16	10.59

*THE EJECTORS LISTED IN THIS TABLE WERE SELECTED TO REPRESENT THE MAJOR CHANGES IN EJECTOR DESIGN WHICH LED TO THE FINAL EJECTOR CONFIGURATION.

TABLE 4

(Sheet 2 of 2)

EJECTOR TYPE	NOZZLE PRESSURE (PSID)	NOZZLE FLOW (ACFM)	EJECTOR FLOW (ACFM)	SYSTEM ΔP (in H_2O)	DEPTH (FSW)	GAS		EFFICIENY
						MIX	% BY VOLUME	RATIO
TAPER NOZZLE (INTERNAL STEPS) 0=.035T/T=.312L/G =.156	60.55	0.59	5.79	8.65	380	HeO_2	84/16	9.82
	80.80	0.69	6.75	10.87	380	HeO_2	84/16	9.84
	99.40	0.76	7.42	12.68	380	HeO_2	84/16	9.70
	135.00	0.90	8.54	16.15	380	HeO_2	84/16	9.47
	60.15	0.55	5.33	8.80	450	HeO_2	84/16	9.73
	80.40	0.64	6.25	11.16	450	HeO_2	84/16	9.82
	102.40	0.72	7.16	13.39	450	HeO_2	84/16	9.89
	135.30	0.83	8.15	16.58	450	HeO_2	84/16	9.78
DOUBLE TAPER NOZZLE (LONG THROAT) 0=.028TT22/ .312L/G=.156	80.54	0.51	7.37	8.82	250	HeO_2	84/16	14.37
	74.81	0.49	6.97	8.21	250	HeO_2	84/16	14.25
	60.03	0.44	6.54	7.15	250	HeO_2	84/16	14.84
DOUBLE TAPER NOZZLE (SHORT THROAT) 0=.028TT22ST312FC	60.79	0.441	5.86	6.54	250	HeO_2	84/16	13.28
	70.97	0.523	6.50	7.64	250	HeO_2	84/16	12.44
	80.05	0.561	6.66	8.33	250	HeO_2	84/16	11.87
	70.31	0.438	6.46	8.16	380	HeO_2	90/10	14.76
	80.56	0.469	7.03	9.56	380	HeO_2	90/10	14.97
	90.83	0.498	7.51	10.28	380	HeO_2	90/10	15.09
	70.06	0.401	6.27	8.53	450	HeO_2	90/10	15.66
	79.98	0.430	6.59	9.59	450	HeO_2	90/10	15.35
	88.97	0.452	6.94	10.32	450	HeO_2	90/10	15.35

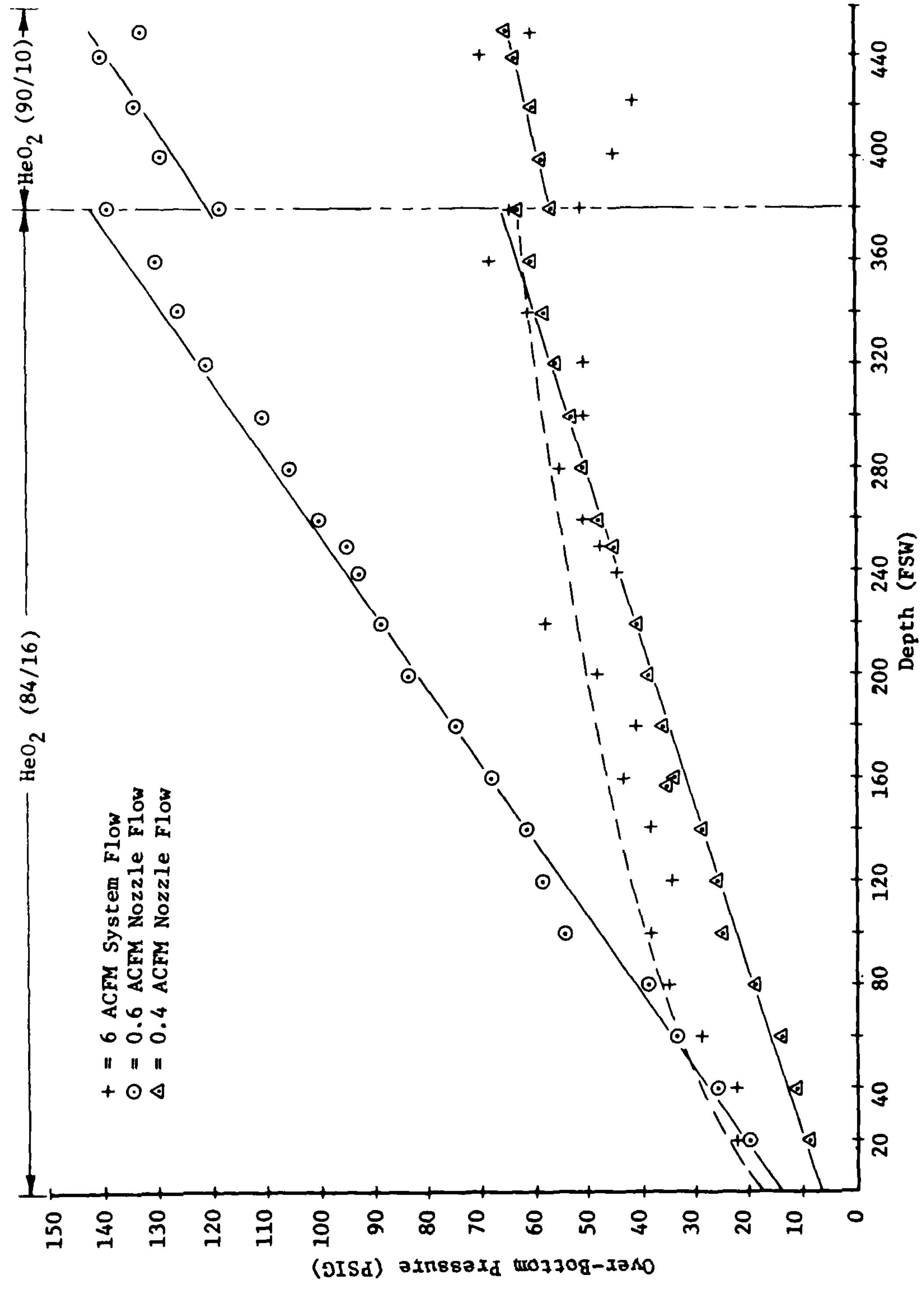


FIGURE 20. PERFORMANCE CHARACTERISTICS OF MK 12 FINAL DESIGN

Approach. Table 5 is an outline of the diagnostic CO_2 scrubber tests. All canisters had absorbent material samples taken for chemical analysis of percent reactivity and percent water content by weight; Figure 21 compares the residual chemical activity/moisture analyses at three locations in a spent canister[14].

Table 6 compares canister bed temperatures of selected tests. Also shown is manned test data depicting gas percent relative humidity (RH) readings at the canister inlet hose.

Results. In the 55°F (12.8°C) temperature range of the bath it became apparent that the midsection of the absorbent bed was being excessively dried. This drying is the result of the temperature gradient between the inlet gas and active-bed temperatures. (NOTE: The absorption of CO_2 is an exothermic reaction.) As the cool inlet gas (typically 100 percent RH at 59°F (15.0°C) enters the active zone of the absorbent bed it is heated by the reaction and passes through the remainder of the bed absorbing moisture in its path. Eventually, when the reaction starts migrating downward, the unused reagent below the preliminary active zone is too dry to support the necessary reaction and CO_2 absorption diminishes. Table 7 is a comparison of canisters with different bed temperatures/durations. Appendix B contains a more detailed analyses of the MK 12 CO_2 scrubber development.

Canister Modification Objective. An attempt was made to reduce the temperature gradient between the inlet gas and mid-bed of the canister.

Approach. The insulation was removed from the canister and tests were run with and without condensers installed in the bed. A slight improvement in canister performance was achieved after some modification to the condensers which eliminated channeling problems. However, further testing indicated that the removal of the insulation caused a second problem. The outer approximately 1-inch (2.54 cm) of the bed closest to the canister wall was absorbing more condensate than the center of the bed. This resulted in the center core of the bed having less flow resistance and therefore even higher gas flow. This "snowballing" of the flow through the center of the absorbent bed practically cancelled out the benefits of reducing the temperature gradient.

The entire canister assembly was inverted in Test No. 12 of Table 5; i.e., system flow directed from the bottom towards top, which indicated a substantial increase in performance. System interface requirements prohibited incorporating this system flow direction reversal into the MK 12 CO_2 scrubber design. It is speculated that the gas flow direction and opposed gravitational forces balanced each other to some degree in maintaining some of the free water in the active portion of the absorbent bed. Task schedules prohibited further investigation of this phenomena.

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[14] Hydrospace Laboratory Note 25-77, Index No. 35, *MK 12 SSDS Recirculator Functional Characteristics Test,* by G. W. Noble, July 1977.

TABLE 5

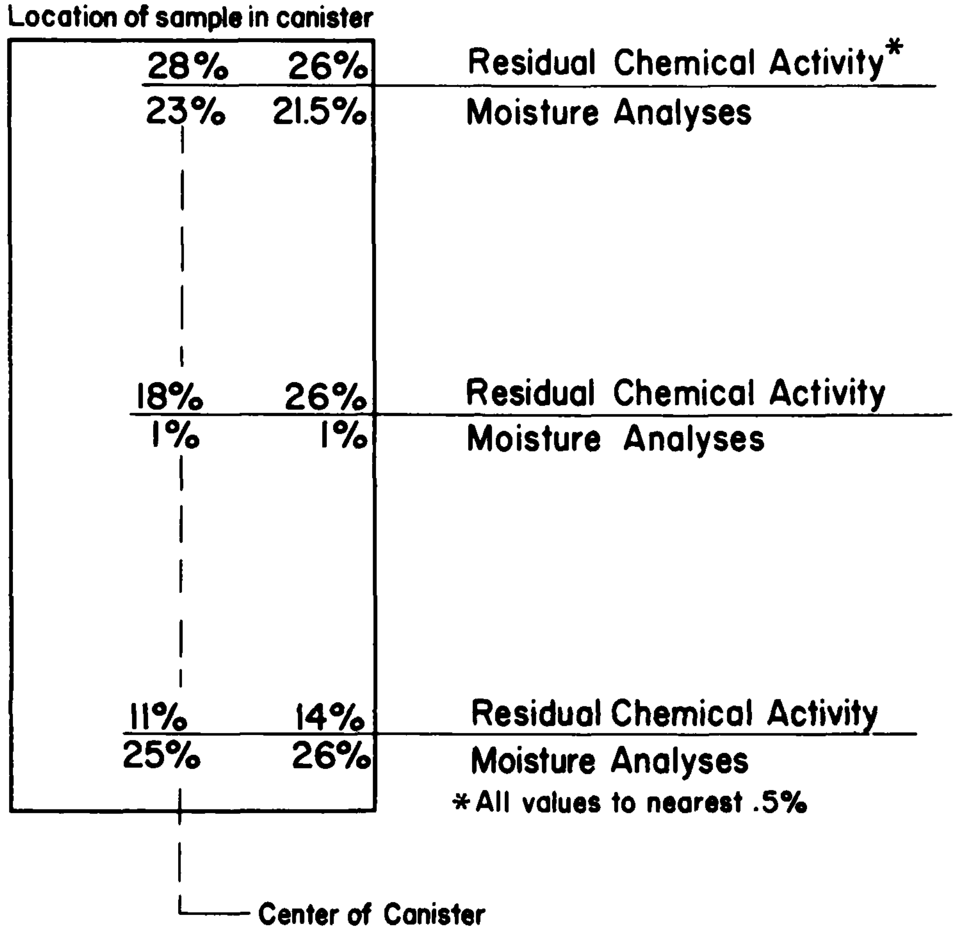
MK 12 DIAGNOSTIC CO_2 SCRUBBER TESTS
(Sheet 1 of 2)

TEST NO.	TEST OBJECTIVES	DURATION (HOURS)	TEST RESULTS
1	Duplicate cyclic CO_2 injection rates of OSE manned dive.	[illegible]	Injection method is a suitable simulation of OSE manned dive.
2	Develop a constant CO_2 injection rate suitable for use in this test.	3.83	Constant CO_2 injection rate of 1.6 LPM simulates manned dive results.
3	Change baralyme lots-reduce possibility of defective baralyme causing short duration - use Test No. 2 procedure.	2.75	No improvement.
4	Evaluate canister without Impreglon coating. Determine if coating enhances channeling.	2.59	No improvement.
5	Change baralyme lots-reduce possibility of double failure causing short duration -use Test No. 4 procedure.	2.84	No improvement.
6	Simulate unmanned test of 12/76.	3.42	No improvement.
7	Thicken insulation and increase bath temperature to 76°F to evaluate effect of higher temperature. Flow meter added to check system flow.	9.0	Conditions provide desired duration.
8	Evaluate effect of reduced bath temperature (56°F) on Test No. 7 configuration.	3.25	Short duration.
9	Attempt to maintain higher gas temperature with additional insulation of ejector and muffler.	3.34	Minimal increase in temperature. No improvement in duration.
10	Ensure adequate humidifier functioning by increasing humidifier temperature. System flowmeter removed.	3.34	No improvement.
11	Evaluate effect of removal of humidifier from the system.	3.17	No change.
12	Evaluate operation with recirculator assembly inverted; humidifier reinstalled.	5.42	Approximately [illegible] increase in canister duration.
13	Evaluate operation with recirculator assembly inverted; NO humidifier.	2.9	Decrease in duration.
14	Evaluate reduction of scrubber bed temperature by removing canister insulation.	4.33	Decrease in duration.

TABLE 5

(Sheet 2 of 2)

TEST NO	TEST OBJECTIVES	DURATION (HOURS)	TEST RESULTS
[illegible]	Retain condensate in scrubber by positioning screens in bed.	-	Inconclusive - apparatus malfunctioned - test stopped.
16	Repeat Test No. 15 setup.	4.51	Approximately 30% increase in canister duration.
[illegible]	Reduce temperature gradient between inlet gas point and mid-bed location.	2.55	Unsatisfactory - condenser produced channeling action.
18	Increase scrubber bed moisture by adding 200 ml of water.	9.0	Good duration - erratic performance.
19	Reduce temperature gradient between inlet gas point and mid-bed location.	2.25	No improvement in duration; slight improvement in bed condition.
20	Evaluate alternative method (spraying) of adding 150 ml of water to bed.	2.5	No improvement.
[illegible]	Evaluate operation using high-water content sodasorb (15-19% water by weight) and condensers.	4.25	Approximately 30% improvement in duration.
22	Evaluate effect of reducing baralyme (time filled 3 [illegible]) and reducing gas residence time [illegible] second in bed.	1.50	Marked decrease in scrubber duration.
[illegible]	Evaluate modified condensers in high water content sodasorb.	3.75	No improvement in duration. Excessive condensate noted near canister wall. High gas flow in the canister bed.
[illegible]	[illegible] canister to allow [illegible] better flow distribution. Repeat Test No. [illegible] setup plus insulation.	7.0	Canister duration increased
[illegible]	[illegible] Test No. [illegible] setup using [illegible].	3.50	Baralyme duration 50% less than high water sodasorb.
[illegible]	[illegible] condensers [illegible] Test No. 24 [illegible].	10.0	Greatly increased duration - CO2 levels still acceptable after 10 hours of operation.



* All Values to Nearest 0.5%

FIGURE 21. CANISTER CONDITION AT CO_2 BREAKTHROUGH

TABLE 6

CANISTER BED TEMPERATURE COMPARISONS

A. SCRUBBER MID-BED TEMPERATURES (UNMANNED)

DATE	BATH TEMP °F	DEPTH	BED TEMP °F	TIME INTO TEST AT READING (HRS)	DURATION OF TEST (HRS)
*12/18/76	40 Inlet Gas Temp 50	Surface	High 59 Low 51 Avg 55	1 9	9
**4/15/77 #12	56	Surface	High 94 Low 84 Avg 89	0.5 5	5.4
**4/28/77 #13	56	Surface	High 91 Low 79 Avg 85	0.5	2.9
*12/17/76	70 Inlet Gas Temp 74	Surface	High 92 Low 79 Avg 86	0.5 6.5	9
*3/30/77 #7	76	Surface	High 91 Low 83 Avg 87	1.25 8.59	9

LEGEND

*Test Configuration Had 6 Thermistors in Canister
**Temperature verified with hard-wire thermistor

B. HUMIDITY READINGS SURFACE (MANNED)

DATE	BATH TEMP (°F)	PROBE TEMP (°F)	RELATIVE HUMIDITY (%)
5/4/77	42	50	98.3
5/3/77	80	79	99.4
5/3/77	(Dry) Air Temp 85	82	68.0
**5/3/77	(Dry) Air Temp 85	82	88.3

LEGEND

**Reading Taken After 2 Minutes of Moderate Work

TABLE 7

RELATIVE HUMIDITY (RH) PERCENT OF GAS IN MK 12 CO_2 SCRUBBER

Test Data	Temperature (°F) (°C)	Inlet Gas (% RH)	Bed Temperature (°F (°C)	Bed* Gas (% RH)	Duration of Test (Hours)
4/28/77 (#13) 56°F 13.3°C Bath	64 17.8 (Estimated) †	100	High 91 32.8 Low 79 26.1 Avg. 85 29.4	42 60 50	2.9
3/30/77 (#7) 76°F 24.4°C Bath	76 24.4 (Estimated) **	100	High 91 32.8 Low 83 28.3 Avg. 87 30.6	65 80 72	9
12/18/76 40°F 4.4°C Bath	50 10.0	100	High 59 15.0 Low 51 10.6 Avg. 55 12.8	70 95 90	9
12/17/76 70°F 21.1°C Bath	74 23.3	100	High 92 33.3 Low 79 26.1 Avg. 86 30.0	59 85 69	9

†Helmet Inside Temperature 68°F (20.0°C)
*Based on NCSL Report 122-72, June 1972, Universal Humidity Chart
**Helmet Inside Temperature 77°F (25.0°C)

The final approach was to re-insulate the canister to maintain better flow distribution and to use a high-water content CO_2 absorbent in conjunction with condensers in the canister to regulate the moisture in the bed.

Results. Further manned testing at NEDU revealed another shortcoming of the MK 12 CO_2 canister. Earlier manned tests, and therefore unmanned simulation, had been conducted using a chill bath temperature of 50°F (10.0°C). Manned dive protocol was changed to specify a chill bath temperature of 40°F (4.4°C). The following excerpt is from NEDU Report 2-78[16]:

"... *The mean of all canister studies at depth was* 255 ± 55 *minutes. It is apparent from the above results that the capability of the prototype MK 12 SSDS is inadequate to support a diver performing prolonged moderate work during an operational dive which could easily last more than six hours. The results do, however, lend insight into a basic problem of carbon dioxide absorption in cold water.*

"Two findings of interest that emerged from the canister breakthrough studies were the increased duration of action of the absorbent bed in warmer water, and a return to higher efficiency during diver turn-over in two of the canister studies. The first finding came as no surprise and is well supported in the literature. The second finding, however, was a surprise during data collection, but upon reflection made sense. In each canister study, absorbent activity began in 29.4°C chamber for several minutes prior to being immersed in cold water. If degradation of canister function occurred as a result of absorbent bed cooling rather than by chemical exahustion, one would expect that a return to 29.4°C chamber and continued scrubbing activity would restore bed activity. This is what was observed, and the conclusion is that the degradation of canister function is not only secondary to chemical exhaustion, but also due to slow cooling of the absorbent bed.

SUMMARY

"The Prototype MK 12 SSDS helium-oxygen recirculating mode was evaluated at its operational depth. The results clearly demonstrated that while the system can support a diver performing heavy work, it cannot support a diver in cold water for sufficient time to complete an operational dive at normal working depths. Since the results support the conclusion that the degradation of canister bed efficiency is due in part to a slow cooling of the absorbent bed, improvements in the canister should include improved thermal protection of the canister and possible gas heating."

Figures 22 and 23 represent typical canister CO_2 signatures during these manned tests. In Figure 23, the second breakthrough curve shows the recovery of the canister during diver change-over. The process of placing a fresh subject (diver) in the system being tested (MK 12) took place in the OSF "trunk"

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(16) Navy Experimental Diving Unit Report 2-78, *Second Manned Evaluation of the Prototype MK 12 SSDS Helium-Oxygen Mode*, by R. K. O'Bryan, March 1978.

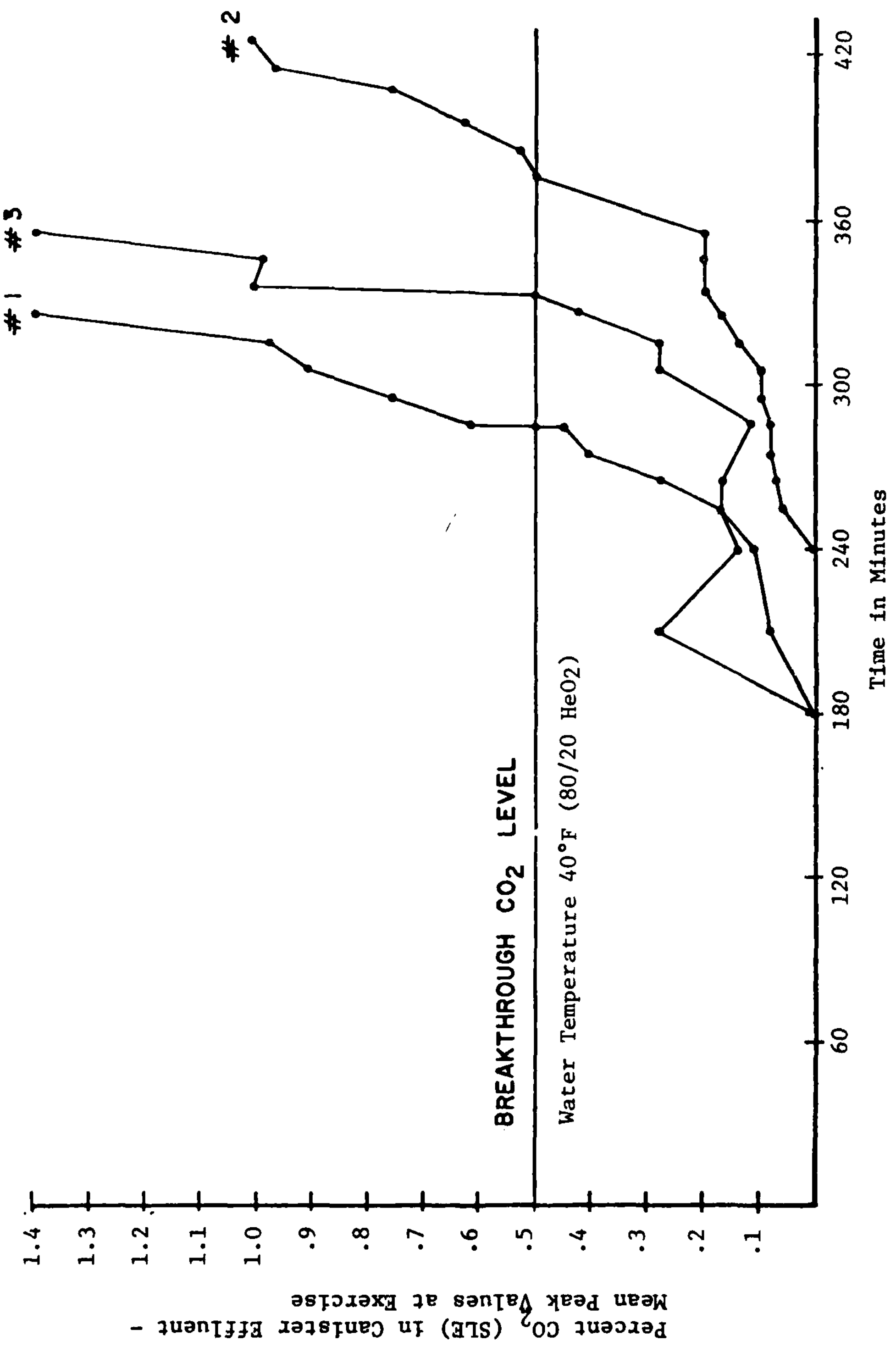

FIGURE 22. MK 12 MANNED CANISTER CO_2 SIGNATURE, 9.8 MSW (32 FSW)

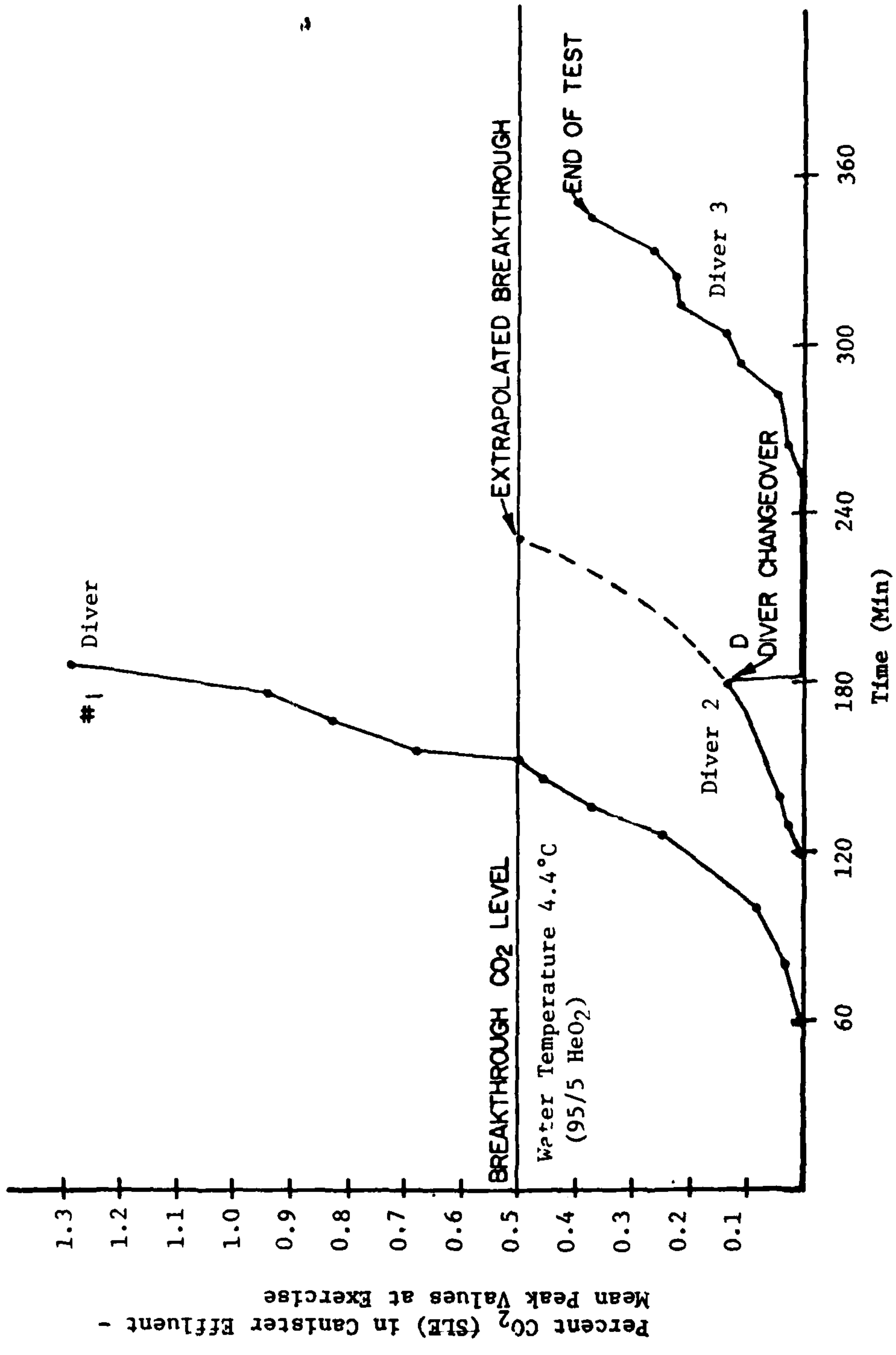

FIGURE 23. MK 12 CANISTER CO_2 SIGNATURE, 121.9-137.2 MSW

which was approximately 80°F (26.7°C) and required about 10 minutes to accomplish. The area of canister thermal protection was addressed based on the results of the tests.

Thermal Protection Objective. The objective of these tests was to optimize the thermal protection of the MK 12 CO_2 scrubber.

Approach. Continued unmanned testing indicated a severe decrease in absorbent material efficiency below a chill bath of 45°F (7.2°C)[14]. A series of manned pool dives were conducted to evaluate methods of heating the canister and gas. The results of these tests are summarized in Table 8; dive profiles are provided in Appendix C.

Figures 24 and 25 show the gas heater, canister lid, and final configurations, respectively (also refer to Figure 17). Canister gas-out CO_2 levels and temperatures inside the backpack and recirculator were recorded. See Appendix C, Figure C-1, for location of thermistors and recorded data.

Results. During the early test dives (Test No. 71 to No. 76), several different gas and canister heating techniques were tested, but the desired dive duration was not reached (Table 8). A 9-hour dive was first achieved in Test No. 77. The configuration consisted of a hot water heated canister top, similar to that shown in Figure 25, shrouds on the helmet inlet and outlet hoses, and a 12-pound canister. In subsequent test dives, the canister top was used at both lower and higher temperatures. Eight of 11 dives met or exceeded the 9-hour requirement. All dives are summarized in Table 8; dive profiles are provided in Appendix C.

Almost all of the 9-hour duration dives were made using high performance sodasorb as the CO_2 absorbent, although a 9-hour dive was also accomplished using medical-grade sodasorb.

Heating the canister top and the interior of the recirculator case was an effective means of ensuring that the CO_2 absorbent chemical reaction continued for the dive duration.

Because of the excellent life results at water temperatures between 35°F (1.7°C) and 40°F (4.4°C), an unscheduled life dive in 29°F (-1.7°C) water at 10 FSW (3.0 MSW) was conducted. Duration of this dive (Table 8, Test No. 91) was 9 hours with no trace of CO_2 at dive completion; however, the water bath temperature increased to 39°F (39°C) over the 9 hours because of pool size and effect of adding hot water for both recirculator and diver heating.

During this test period, a single MK 12 recirculator made 88 dives for a total of 155.2 hours without a MK 12 system abort. In addition, the same equipment was used for 10 brief training dives.

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[14] ibid.

TABLE 8

SUMMARY TEST RESULTS (Sheet 1 of 2)

Date 1978	Test No.	Absorbent BR, SS, HP	Depth FSW	Water Temp. °F (°C)	Work Rate Watts	Duration Hrs.	Remarks
1-19	72	HP	10	39 (3.9)	50	4.75	Kinergetics gas heater, HEX 5 Model 3330 installed in place of muffler using 9 lb. canister.
1-20	73	HP	10	37 (2.8)	50	2.8	Kinergetics gas heater installed on top of 9 lb. canister. Aborted due to excess moisture in helmet breakthrough estimated in 1/2 hour more operation.
1-23	74	HP	10	38 (3.3)	50	6.5	Same as Test No. 72 using 12 lb. canister.
1-24	75	HP	10	38 (3.3)	50	4.4	Kinergetics gas heater modified, with all but 8 elements removed. 12 lb. canister.
1-25	76	HP	10	37 (2.8)	50	7.8	Same as Test No. 75 with all but 3 elements removed 12 lb. canister.
1-26	77	HP	10	38 (3.3)	50	10.0	12 lb. canister with 4 screen elements in lid. Hot water flow through 1/4" copper tubing. Rigid hoses shrouding helmet inlet and outlet hoses.
1-30	78	HP	10	38 (3.3)	50	9.0	12 lb. canister with modified cap on canister lid. Rigid hoses shrouding helmet inlet and outlet hoses.
1-31	79	HP	10	39 (3.9)	50	6.5	Same as Test No. 78 using 9 lb. canister.
2-1	80	HP	10	51 (15.5)	50	9.0	Same as Test No. 78.
2-2	81	HP	10	50 (10.0)	50	9.1	Same as Test No. 78. No hot water.
2-3	82	HP	10	50 (10.0)	50	6.25	Same as Test No. 78. No hose shrouds. Aborted due to broken ergometer with 0.1% CO_2 SLE.
2-6	83	HP	10	40 (12.2)	50	9.0	Same as Test No. 78 except neoprene dry suit material shrouds over helmet inlet and outlet hoses.

TABLE 8 (CONT'D)

(sheet 2 of 2)

Date 1978	Test No.	Absorbent BR, SS, HP	Depth FSW	Water Temp. °F	(°C)	Work Rate Watts	Duration Hrs.	Remarks
2-7	84	HP	10	39	(3.9)	50	9.0	12 lb. canister using modified cap on canister lid and neoprene shroud. Lost hot water 6.5 hrs. Final CO_2 SLE 0.2%.
2-8	85	HP	10	45	(7.2)	50	7.6	Same as Test No. 84 with 9 lb. canister. No heating.
2-9	86	Medical-Grade SS	10	50	(10.0)	50	9.0	Same as Test No. 84. No heating.
2-10	87	Baralyme	10	50	(10.0)	50	6.0	Same as Test No. 84. No heating.
2-13	88	HP	10	71-85	(21.7-29.4)	50	9.0	Same as Test No. 84. No heating.
2-14	89	HP	10	NA		NA	NA	Same as Test No. 84. Human engineering test.
2-15	90	HP	5	29	(-1.7)	50	2.0	Same as Test No. 84. Functional cold water test. No heating. At 2.0 hrs no trace CO_2.
2-16	91	HP	5	29-39	(1.7-3.9)	50	9.0	Same as Test No. 8. Hot water to diver recirculator.

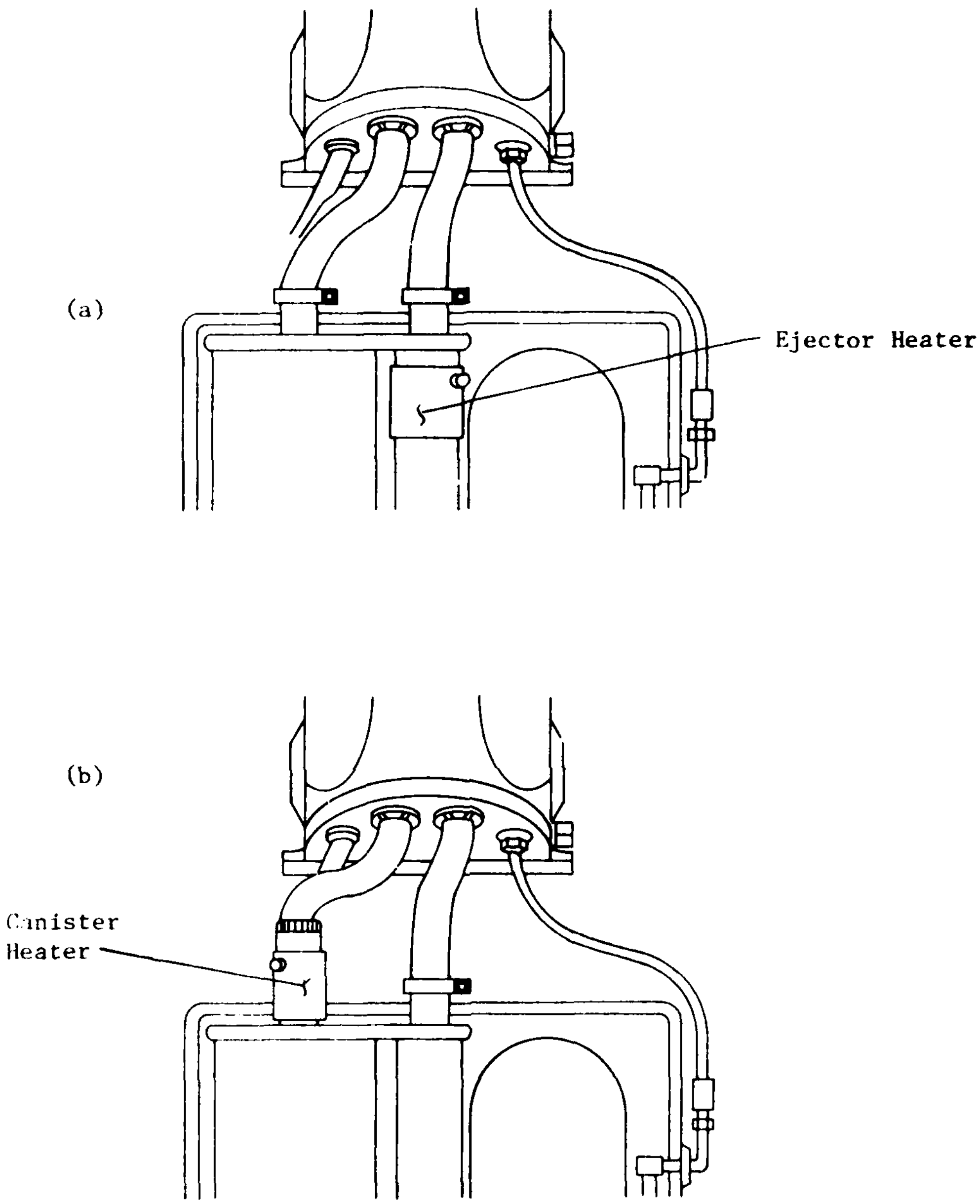
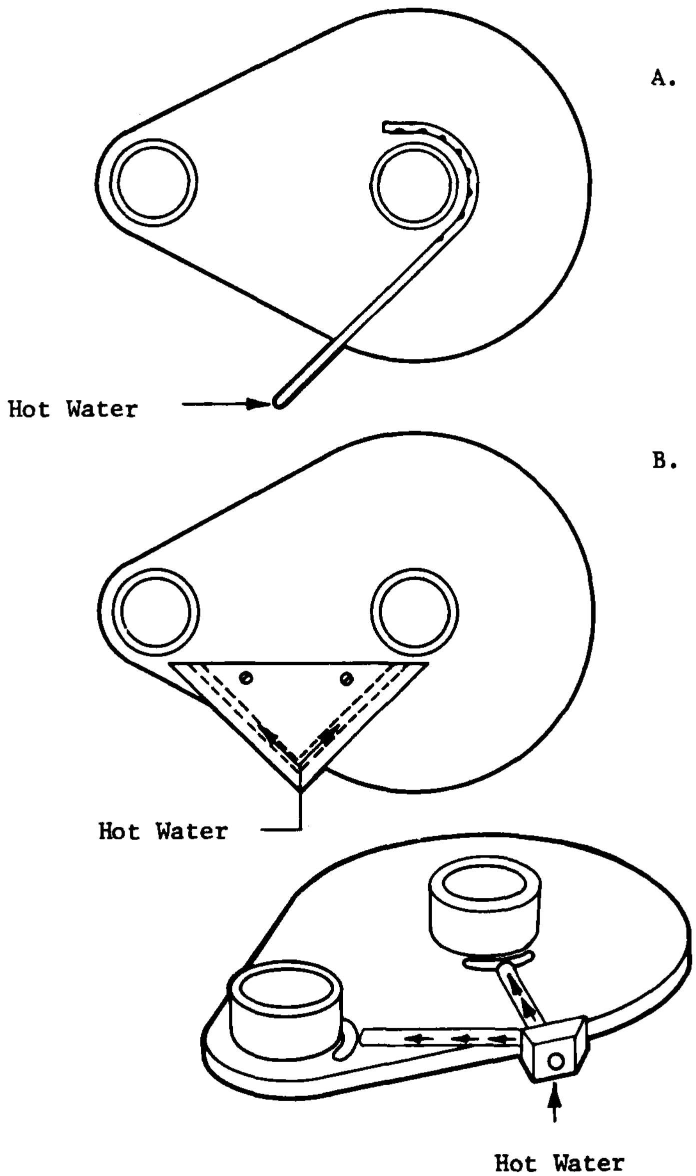


FIGURE 24. KINERGETICS GAS HEATER INSTALLED (INLET AND EXHAUST)



A. 1/4" Copper Tube Hot Water Flow Through Ten 1/16" Diameter Holes Around and Over Canister Top. Used in Test No. 77

B. Flanged Plate Directing Hot Water. Used in All Tests After Test No. 77

C. Final Configuration

FIGURE 25. CANISTER TOP HOT WATER PORT CONFIGURATIONS

Conclusions. The recirculator configuration used in Test No. 78 (Table 8) and subsequent dives demonstrated consistent, long canister life. In this configuration, a hot water flow was directed at the recirculator inlet/outlet hoses and then was exhausted into the recirculator case/shrouds. This flow path and temperature distribution inside the case produced conditions conducive to desired CO_2 scrubbing action in the recirculator at the test temperatures. On 6 February 1978, the recirculator design was frozen on this concept. A schematic illustration of the canister top is shown in Figure 25. Figure 6 illustrates the final recirculator design concept. The modified recirculator demonstrated the required 9-hour duration in water above $50^{\circ}F$ ($10.0^{\circ}C$) without hot water heating.

High performance and medical-grade sodasorb provided longer canister durations than baralyme under the same test conditions. However, the tests of both medical-grade sodasorb and baralyme are inconclusive, since only one test of each material was conducted. Past unmanned tests indicate that medical-grade sodasorb has demonstrated a 9-hour canister life capability in a water temperature of $50^{\circ}F$ ($10.0^{\circ}C$), and this absorbent should be satisfactory for the MK 12 recirculator. It may be concluded that baralyme is suitable for use in the MK 12 recirculator in dives of less than 6 hours duration.

Breathing Gas Heater Evaluation

Objective. The objective of this test phase was to evaluate direct gas heating as a means to extend canister duration in cold water diving; i.e., below $50^{\circ}F$ ($10.0^{\circ}C$), in lieu of flooding the backpack with hot water.

Approach. Kinergetics gas heater, HEX-5 Model 3330, was used for the evaluation. The heater was inserted in place of the ejector muffler for Test No. 72 and No. 74 (Figure 24a). For Test No. 73, the heater was placed on top of the canister (Figure 24b). In addition, the number of heating elements used in the heater on the canister top configuration was varied in Test No. 75 and No. 76.

Results. Use of the gas heater in any of the configurations and in conjunction with the large canister did not obtain the required canister life of 9 hours. When the gas heater was used in place of the ejector muffler, the temperature drop across the recirculator inlet and outlet hoses and the helmet resulted in previously heated gas re-entering the canister at ambient temperature. When the gas heater was tested on top of the canister, the heated gas dried out the absorbent bed and forced the bed moisture through the ejector into the helmet. As the absorbent bed dried, canister efficiency was reduced.

As testing progressed, use of hot water heating on the canister inlet and outlet hoses and inside the recirculator case versus direct heating produced better life results for the MK 12 system configuration.

Conclusions. A gas heater of the general type tested does not produce the necessary conditions in the MK 12 system configuration to develop the desired canister durations.

Comments. Figures 15, 16, and 17 show the final design of the corrugated shroud hoses. Figure 26 depicts the MK 12 carbon dioxide absorbent canister.

In July 1978 the MK 12 prototype CO_2 scrubber underwent manned testing in the OSF. The results are described in Reference 16.

> *"Testing of previous prototype MK 12 SSDS carbon dioxide absorbent canisters indicated that initial cooling of exhaled gas with subsequent gas rewarming within the CO_2 absorbent bed led to drying of the absorbent material and deterioration in performance. The first two prototypes tested in manned dives had shorter CO_2 scrubbing durations than desired. The recirculator assembly was modified by incorporation of two moisture retaining condensors within the body of the canister and hot water heating of the canister. Three canister studies were performed in 40°F water at 390 FSW. The divers performed 6-minute work periods, separated by 4 minutes of rest, at a work rate of 50 watts on a pedal ergometer. The work-rest sequence was selected to approximate an average metabolic production of 1.5 liters of CO_2 per minute and simulate a hard working dive. The work-rest sequence proceeded until canister effluent reached 0.5 percent Sea Level Equivalent (SLE) (3.8 mmHg). The mean CO_2 value of the three canisters at 9 hours was 0.2 percent SLE. One study was continued until breakthrough, 0.5 percent SLE, which occurred at 10 hours. It is unlikely that any operational dive would involve continuous, moderate work for 9 hours.*
>
> *"Therefore, the results clearly demonstrated that the MK 12 SSDS helium-oxygen mode would support a diver for the design goal of 9 hours."*

Figure 27 shows the canister breakthrough curves for the final canister CO_2 signature tests. Based on the one canister life that was terminated at 1.0 percent SLE, the efficiency of the absorbent bed is indicated in Table 9.

Canister degradation as a function of depth cannot be plotted due to the lack of data points. Three test configurations were identical or very close to the final design (see Table 8, Test No. 77, No. 78, and No. 83). Comparing test results of the manned pool tests conducted during January and February 1978 to the OSF test dives[16] yields the following comparisons:

Pool Tests	OSF Tests
10 FSW @ 40°F (3.0 MSW @ 4.4°C) SLE CO_2 reading at 9 hours $\bar{X}$ = 0.03%	390 FSW @ 40°F (118.9 MSW @ 4.4°C) SLE CO_2 reading at 9 hours $\bar{X}$ = 0.2%

This would indicate a 15 percent degradation between 10 FSW (3.0 MSW) and 390 FSW (118.9 MSW).

(16)Navy Experimental Diving Unit Report 20-78, *Carbon Dioxide Absorbent Canister Studies of Hot Water Heated Helium-Oxygen Mode,* by W. H. Spaur, E. D. Thalmann, and R. C. Maulbeck, December 1978.

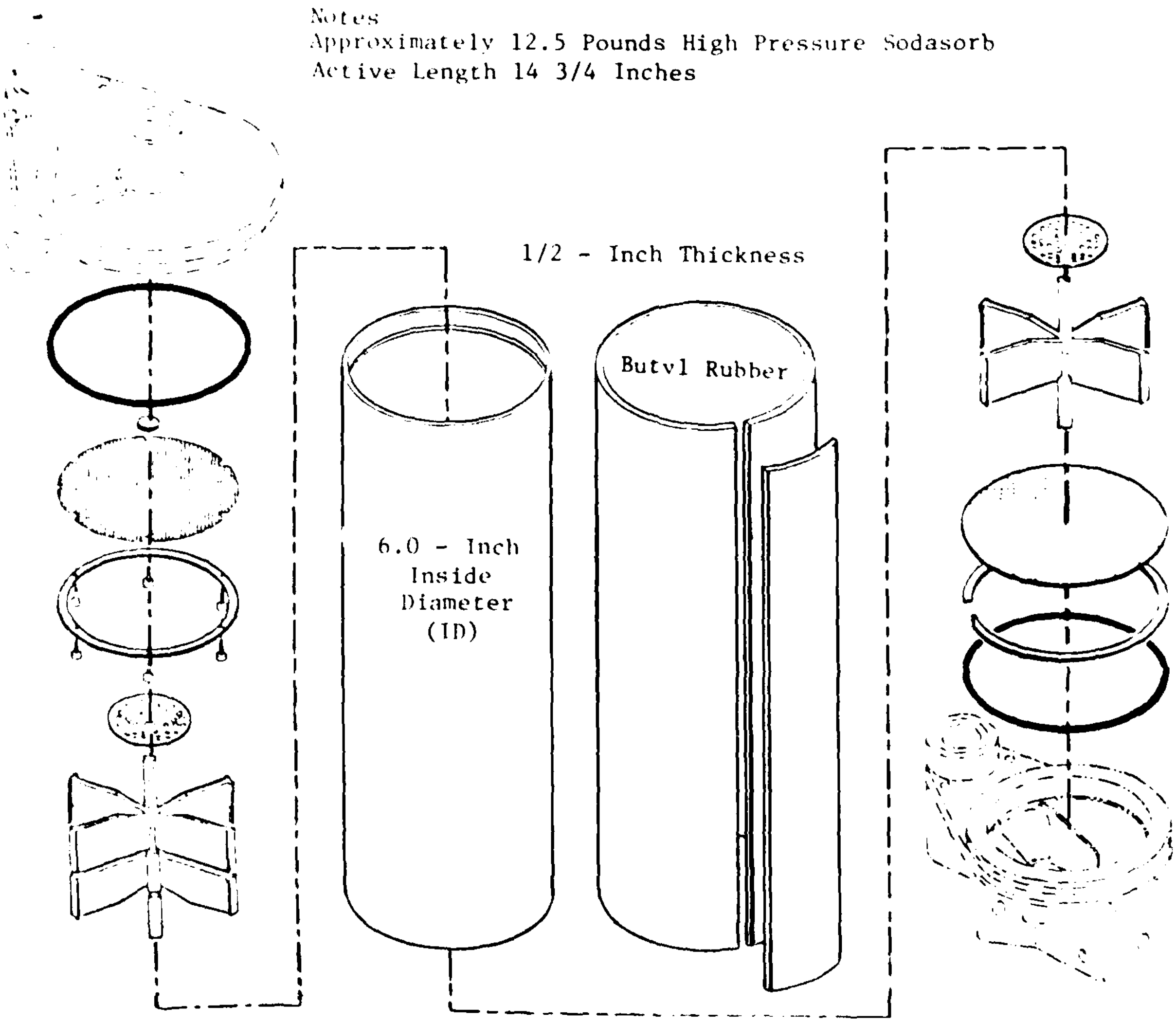


FIGURE 26. CARBON DIOXIDE ABSORBENT CANISTER

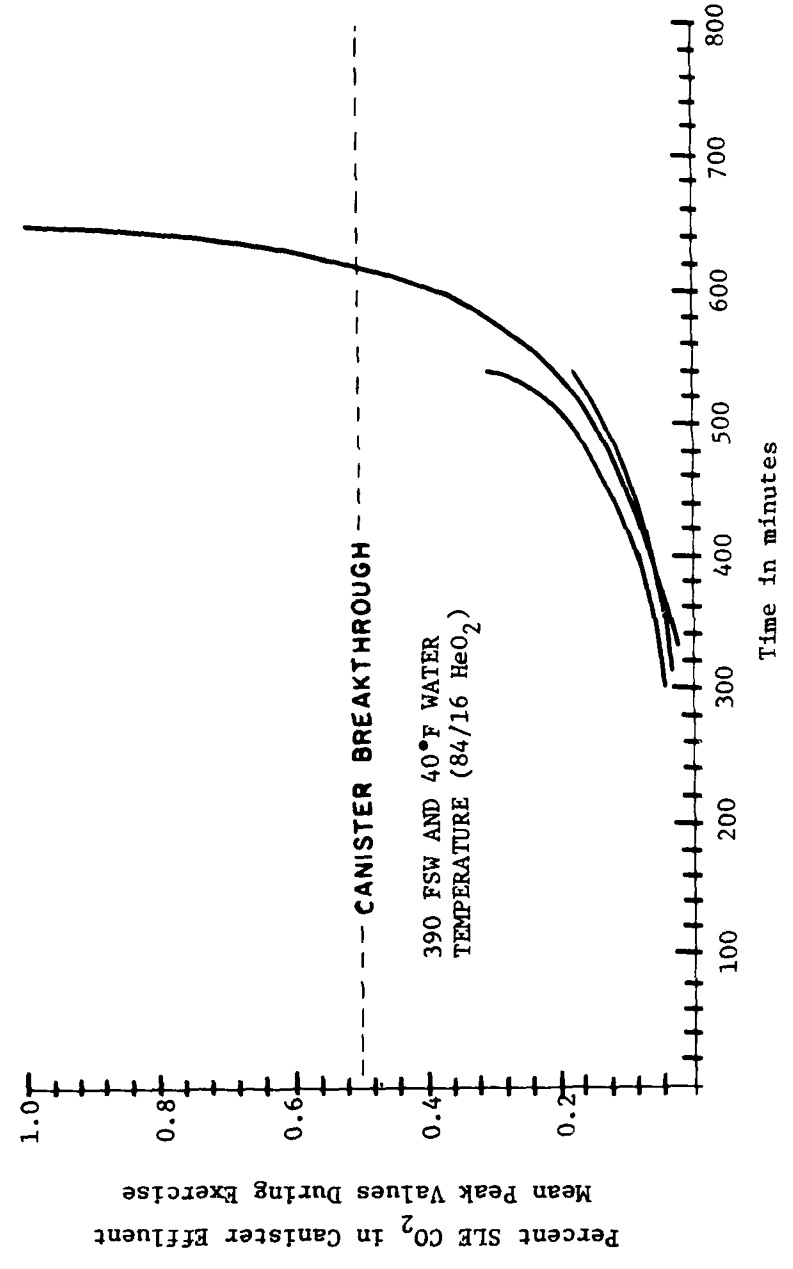


FIGURE 27. FINAL MK 12 MANNED CANISTER CO_2 SIGNATURES

TABLE 9

MK 12 CANISTER EFFICIENCY

1. CO_2 levels into canister (mean values) based on 2/77 NEDU dive.

2. Weight of high performance Sodasorb in MK-12 canister is approximately 12.46 lbs. (5.65 kg)

% CO_2 (SLE)

Rest	50 watts
0.33	0.75

3. Determining the total amount of CO_2 produced by the diver.

Q = 6 ACFM (169.9 ALPM) Flow

ψ = upstream % CO_2 (SLE) ψ_1 -- During rest

ψ_2 -- During work

δ = Density of CO_2 at 1 ATA and $30^{\circ}F$ ($-1.1^{\circ}C$)

= 0.12393 lb/ft^3 (1.98469 kg/m^3)

A test duration of 11 hrs* with 10 min. cycles of 4 min. rest and 6 min. of work yields

264 min. of rest

396 min. of work .

This implies a total mass of CO_2 produced:

$$\psi_1 Q\delta\ (264) + \psi_2 Q\delta\ (396) = 12.46 \text{ lbs } (5.65 \text{ kg})$$

4. Theoretically high performance Sodasorb should absorb 50 percent of its own weight in CO_2, or 6.23 lb (2.83 kg) of CO_2. The MK 12 canister efficiency is therefore approximately 45.8 percent (amount of CO_2 absorbed/theoretical capacity).

*11 Hours to 1.0% CO_2 SLE.

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2. Navy Experimental Diving Unit Report No. 18-78, *Life Support Characteristics of the MK 11 Semi-Closed Mixed Gas UBA at Intermediate Depths,* by C. A. Piantadosi and W. H. Spaur, November 1978.

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11. Hydrospace Laboratory Note 13-76, Index No. 13, *Recirculator Duration Test,* by G. W. Noble, June 1976.

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13. Navy Experimental Diving Unit Report No. 10-77, *Manned Evaluation of the Prototype MK 12 SSDS Helium-Oxygen Mode,* by R. K. O'Bryan, September 1977.

14. Hydrospace Laboratory Note 25-77, Index No. 35, *MK 12 SSDS Recirculator Functional Characteristics Test,* by G. W. Noble, July 1977.

15. Navy Experimental Diving Unit Report 2-78, *Second Manned Evaluation of the Prototype MK 12 SSDS Helium-Oxygen Mode,* by R. K. O'Bryan, March 1978.

16. Navy Experimental Diving Unit Report 20-78, *Carbon Dioxide Absorbent Canister Studies of Hot Water Heated Helium-Oxygen Mode,* by W. H. Spaur, E. D. Thalmann, and R. C. Maulbeck, December 1978.

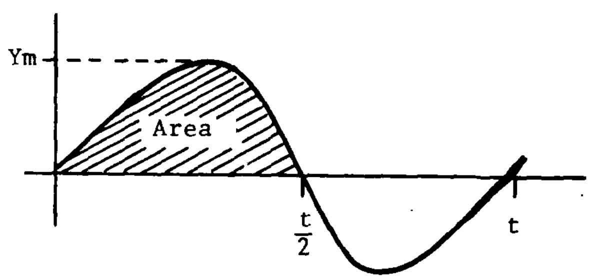
APPENDIX A

MK 11 SYSTEM FLOW ANALYSIS

The normal direction of system flow is from the exhalation bag through the canister and into the inhalation bag. Simultaneously, fresh gas is being injected through the sonic orifice and into the inhalation bag. During unmanned testing of the MK 11, it was observed that at specific times in the breathing cycle system flow direction reversed. The flow reversal process is depicted in Figures A-1 and A-2 as a negative flow.

The duration of the CO_2 scrubber is directly proportional to the amount (mass) of CO_2 it absorbs. During reverse flow in this system the canister is being presented with gas free of CO_2; i.e., the gas in the inhalation bag consists of fresh make-up gas and gas previously scrubbed of CO_2. Using sine wave approximations for the curves recorded in Figures A-1 and A-2 permits a calculated estimate of actual flow in either direction through the canister per each breath.

Consider an apparent greater amount of reverse flow on the surface as compared to the 305 FSW (93.0 MSW), approximating the curves in question by a sine wave (refer to the dynamic flow plots of Figures A1 and A2).



y_m = max. amplitude

$wt = 2\pi$

$w = \frac{2\pi}{t}$

$$\text{area} = \int_0^{t/2} y_m \sin wt \, dt = -\frac{y_m}{w} \Big|_0^{t/2} \cos wt$$

and

1 breath = 100 data points
at 1 BPM, 1 data point = 0.03 second

which yields:

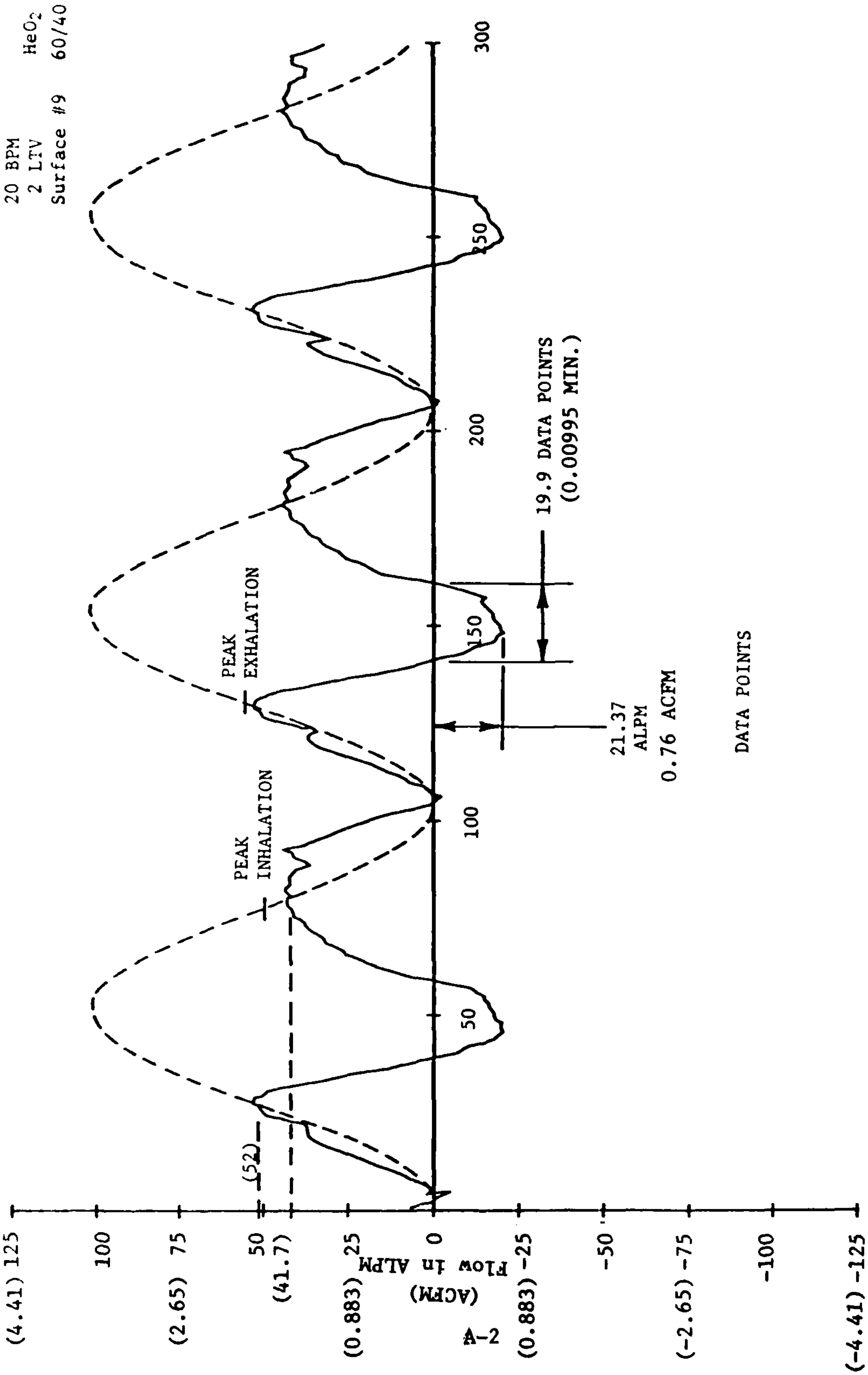


FIGURE A-1. MK 11 REVERSE FLOW TEST (1 ATA)

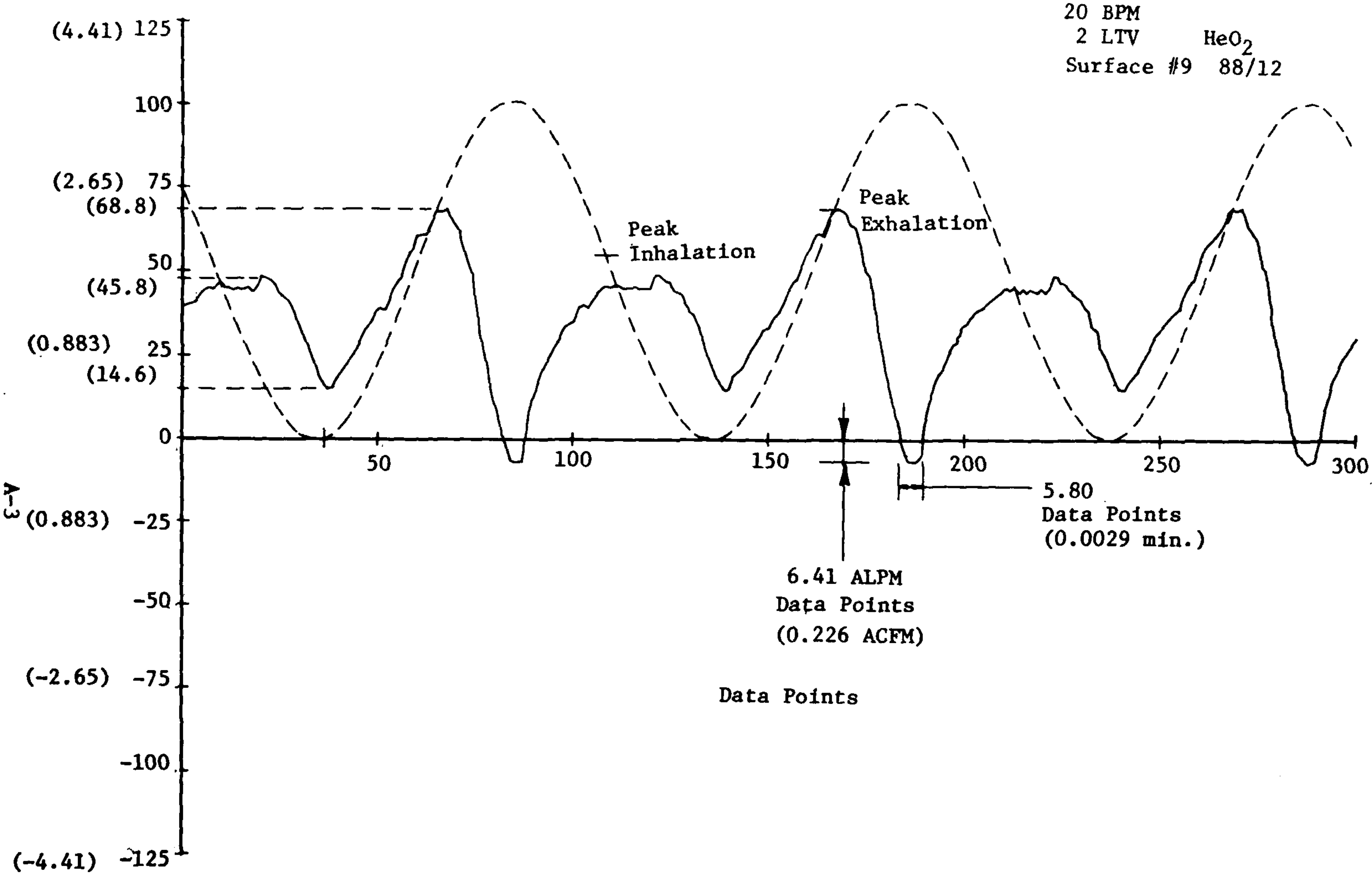


FIGURE A-2. MK 11 REVERSE FLOW TEST (305 FSW)

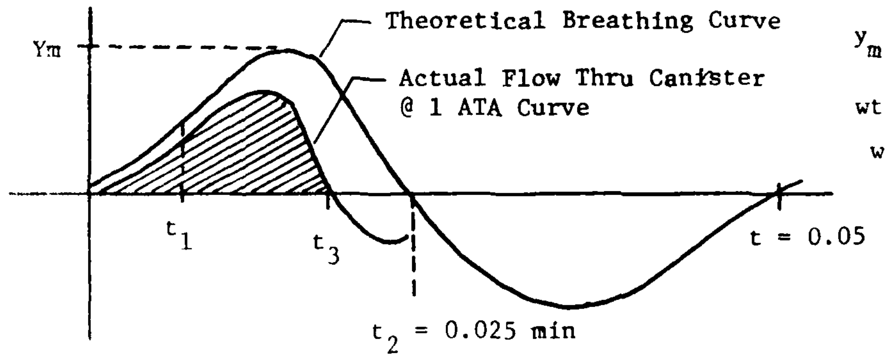
<u>at surface</u>	<u>at 305 FSW (93.0 MSW)</u>
y_m = 21.37 ALPM (0.755 ACFM)	y_m = 6.41 ALPM (0.2263 ACFM)
t/2 = 0.597 sec.	t/2 = 0.174 sec.
t/2 = 0.00995 min.	t/2 = 0.0029 min.
$0.135 \dfrac{\text{actual litre}}{\text{breath}}$	$0.0018 \dfrac{\text{actual litre}}{\text{breath}}$
REVERSE FLOW	REVERSE FLOW
$(0.00477 \dfrac{\text{actual ft}^3}{\text{breath}})$	$(0.0000636 \dfrac{\text{actual ft}^3}{\text{breath}})$

During exhalation at the end of each exhaled breath and the beginning of each inhaled breath

To fill in some estimates on the CO_2 curve: the first 0.150 litre (0.0053 ft^3) of the tidal volume is from dead space in the trachea and contains no CO_2. All CO_2 is contained in the tidal volume less the dead space.

(2 litres - 0.15 litre) = 1.85 litres
(0.0706 ft^3 - 0.0053 ft^3 = 0.0653 ft^3)

For 40 RMV



y_m = 125.66 litre/min
(4.44 ft^3/min)

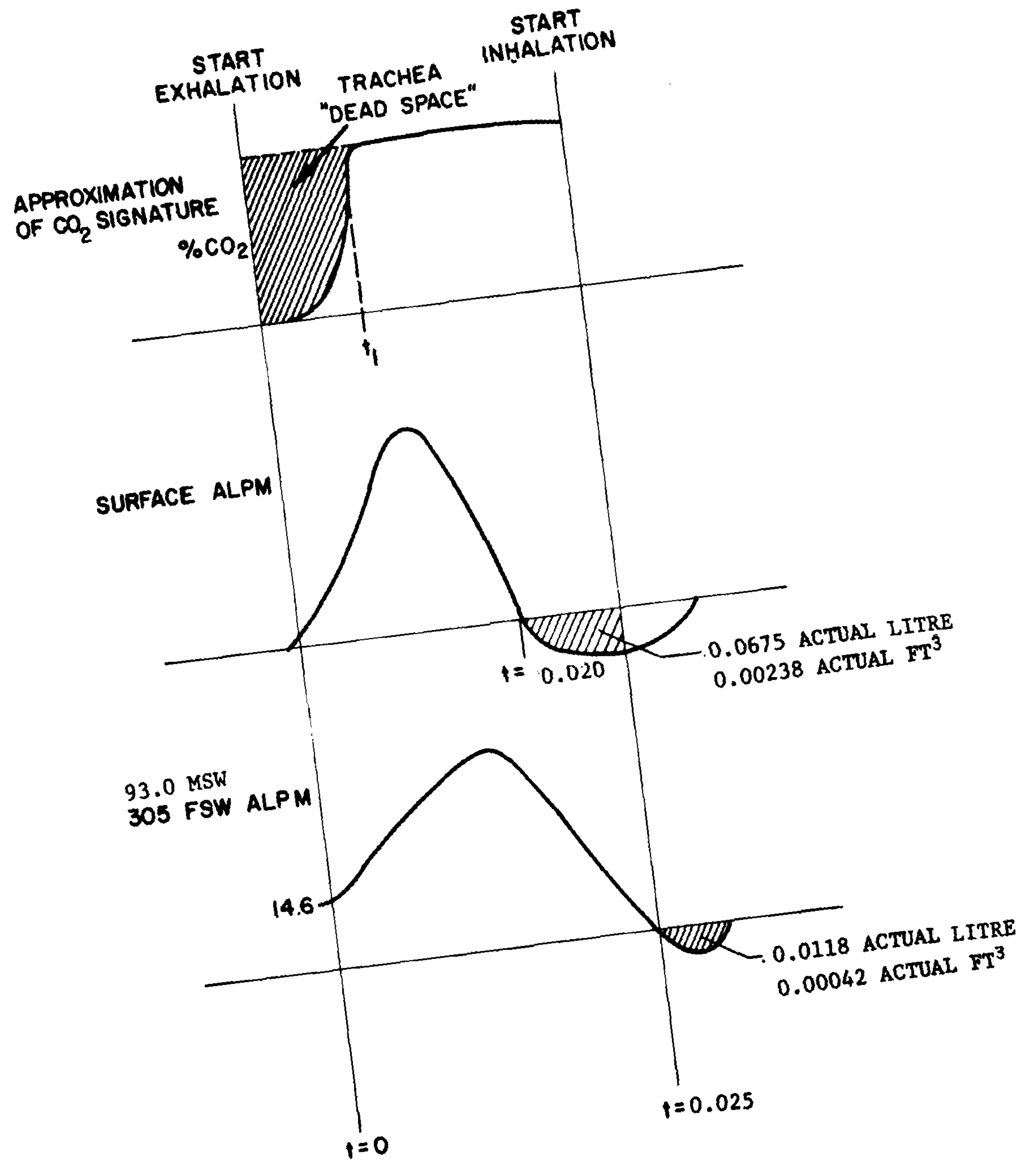
wt = 125.66

$w = \frac{2\pi}{t}$

If we approximate the CO_2 signature by a square wave, then between t_1 and t_2 there is a total of 1.85 litre (0.0653 ft^3) of CO_2 laden gas.

Using a sine wave approximation for the breathing signature, solve for t_1

$$\text{area under breathing} = 1.85 = -\frac{y_m}{w} \Big|_{t_1}^{t = 0.025} \cos wt$$


START EXHALATION
TRACHEA "DEAD SPACE"
START INHALATION
APPROXIMATION OF CO_2 SIGNATURE
%CO_2
t_1
SURFACE ALPM
t= 0.020
0.0675 ACTUAL LITRE
0.00238 ACTUAL FT^3
93.0 MSW
305 FSW ALPM
14.6
0.0118 ACTUAL LITRE
0.00042 ACTUAL FT^3
t=0
t=0.025

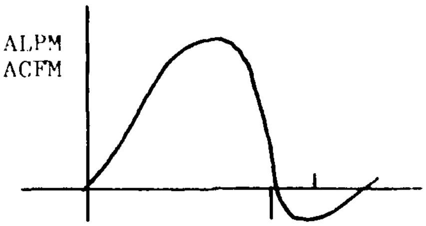
$$1.85 = (-1)\ (\cos \frac{2\pi}{0.05} = 0.25 - \cos \frac{2\pi}{0.05}\, t_1)$$

$$\frac{2\pi}{0.05}\ \frac{t_1}{\min} = 0.1766\ \pi$$

$$t_1 = 0.0044 \text{ min}$$

Now estimate the area under the curve representing canister flow 1 ATA:

EXHALATION



y_m = 52 ALPM (1.84 ACFM)

$wt = 2\pi$

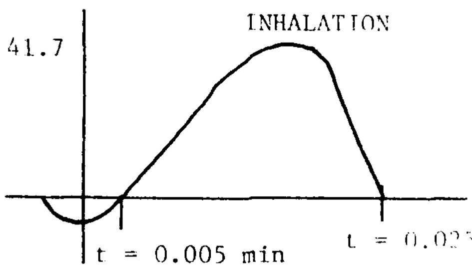
$$w = \frac{2\pi}{0.04} = \frac{\pi}{0.02} = 157.1$$

$$\text{area} = \int_{t_0}^{t\,=\,0.020} y_m \sin wt\ dt = -\frac{y_m}{w} \Big|_0^{0.020} \cos wt = (\frac{52}{157.1}) \Big|_0^{0.020} \cos (\frac{2\pi}{0.04}\, t)$$

$$= -\ (0.331)\ (\cos (\frac{2\pi}{0.04})\ (0.020) - \cos (\frac{2\pi}{0.04})\ (0))$$

area = 0.662 actual litre (0.0234 ft^3) per exhaled breath

INHALATION



y_m = 41.7 ALPM (1.47 ACFM)

$wt = 2\pi$

$$w = \frac{2\pi}{0.04} = 157.1$$

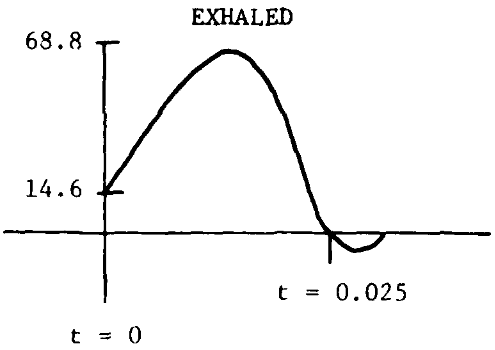
$$\text{area} = -\ (\frac{41.7}{157.1}) \Big|_{0.005}^{0.020} \cos (\frac{2\pi}{0.04}\, t) = -(0.265)\ (-2) = 0.531$$

area = 0.531 actual litre (0.01875 ft^3) per inhaled breath

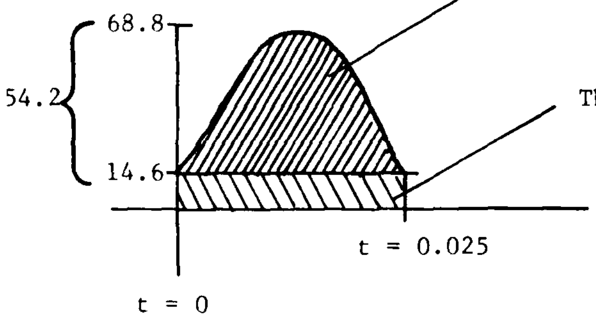
0.662 + 0.531 = 1.193 actual litres breath
(0.0234 + 0.01875 = 0.0423 ft^3)

This implies that 1.193 actual liters (0.0423 ft^3) of CO_2 laden gas passes through the canister during each breath at 1 ATA and 40 RMV.

Now estimate the area under the curve representing canister flow at (10.2 ATA).



For simplicity, consider this curve a sine wave above a constant flow of 14.6 ALPM (.5155 ACFM)



The area of this portion is:

$$-\left(\frac{54.2}{125.66}\right)(-2) = 0.8626 \text{ actual litre } (0.0305 \text{ ft}^3)$$

The area of this portion is:

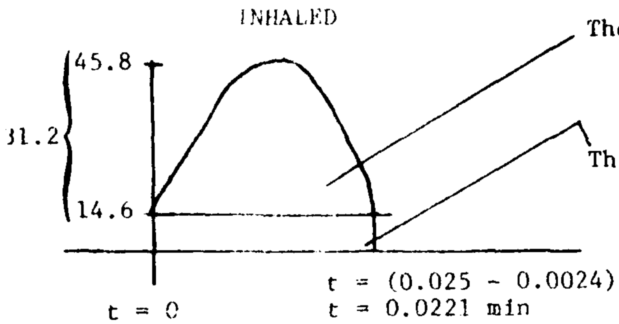
0.365 actual litre (.01289 ft^3)

$y_m = 54.2$

$wt = 2\pi$

$w = \frac{2\pi}{0.05} = 125.66$

Total area = 0.8626 + 0.365 = 1.228 litre (0.0305 + 0.01289 = 0.0434 ft^3
1.228 actual litre (0.0434 ft^3) per exhaled breath.



The area of this portion is:

$$-\left(\frac{31.2}{142.15}\right)(-2) = 0.4390 \text{ litre } (.0155 \text{ ft}^3)$$

The area of this portion is:

0.3227 actual litre (0.01139 ft^3)

$$y_m = 31.2$$

$$wt = 2\pi$$

$$w = \frac{2\pi}{0.0442} = 142.15$$

Total area = 0.4390 + 0.3227 = 0.762 actual litre (0.0155 + 0.01139 = 0.02689 ft^3)

0.762 actual litre (0.0269 ft^3) per exhaled breath

1.288 + 0.762 = 1.989 actual litres/breath

(0.0434 + 0.0269 = 0.0703 ft^3)

This implies that 1.989 actual litres (0.0703 ft^3) of CO_2 laden gas passes through the canister during each breath at 305 FSW (93 MSW) and 40 RMV.

Comparing the flow of make-up gas at 0 MSW (0 FSW) (6.85 ALPM orifice flow) (0.2419 ACFM) and the gas flow at 305 FSW (93 MSW) (2.72 ALPM orifice flow) (0.0960 ACFM):

the total amount of gas removed is as follows:

at 40 RMV the total amount of gas moved is

(20 breaths/min.) (2 litres (0.0706 ft^3) tidal volume) + make-up gas

at 1 ATA

(40 + 6.85) litres = 46.85 litres ((1.41 + 0.24) ft^3 = 1.65 ft^3)

at 305 FSW

(40 + 2.72) litres = 42.72 litres ((1.41 + 0.096) ft^3 = 1.51 ft^3)

which implies:

$$\frac{46.85}{42.72}\left(\frac{1.65}{1.51}\right) = 1.0966 \simeq 110\%$$

The concentration of CO_2 will be 1G percent greater at depth than at the surface (assuming similar mixing of gases).

Combining this information with the canister flow comparisons yields:

$$\frac{1.193}{(1.10)(1.989)} = 0.5469$$

or approximately 55 percent more CO_2 being presented to the canister at depth than at 1 ATA, which implies that:

where the total flow through the canister is forward and reverse flow

<u>at 1 ATA</u>

$$\left(\frac{46.85}{20}\right) - (1.193 \text{ actual litres/breath}) = 1.149$$

$$\left(\left(\frac{1.65}{20}\right) - 0.042 \text{ actual ft}^3 = 0.0406 \text{ ft}^3\right)$$

1.15 actual litres/breath are vented out of the cardiod exhaust valve (0.04 ft^3).

<u>at 305 FSW</u>

$$\left(\frac{42.72}{20}\right) - 1.989 \text{ actual litres/breath} = 0.147$$

$$\left(\left(\frac{1.51}{20}\right) - 0.070 \text{ actual ft}^3\text{/breath} = 0.0052\right.$$

0.15 actual litre/breath is vented out of the cardiod exhaust valve (0.005 ft^3).

APPENDIX B

MK 12 CO_2 SCRUBBER DEVELOPMENT ANALYSIS

Empirical test results of the MK 12 CO_2 scrubber indicated that the mid-section of the absorbent bed was being dried excessively. This drying is the result of the temperature gradient between the inlet gas and active-bed temperatures. (NOTE: The absorption of CO_2 is an exothermic reaction.) As the cool inlet gas (typically 100 percent RH @59°F (15.0°C)) enters the active zone of the absorbent bed it is heated by the reaction and passes through the remainder of the bed absorbing moisture in its path. Eventually, when the reaction starts migrating downward, the unused reagent below the preliminary active zone is too dry to support the necessary reaction and CO_2 absorption diminishes.

Consider 100 percent relative humidity (RH) at an inlet temperature of 60°F (15.6°C) and 100 percent RH in zone of canister which is at 80°F (26.7°C:

80°F	0.0014[B1]	lb H_2O/ft^3	(26.7°C	0.0224	gm/litre)
60°F	0.0007	lb H_2O/ft^3	(15.6°C	0.0112	gm/litre)
	0.0007	lb H_2O/ft^3		(0.01112	gm/litre)

Therefore, the 80°F (26.7°C) zone must provide 0.0007 lb H_2O/ft^3, which at 6 ACFM (169.9 ALPM) (ft^3/min) is:

$$(6\ ft^3/min.)\ (0.0007\ lb\ H_2O/ft^3) = 0.0042\ lb\ H_2O/min$$

$$(0.0112\ gm/litre)\ (169.9\ gm/litre) = 1.903\ gm/min$$

Absorbent material in the 80°F (26.7°C) zone is being dried at a rate of 0.0042 lb H_2O/min (1.903 gm/min).

Absorbent Materials

Baralyme ∿ 12% water — 8% bonded H_2O; 4% free H_2O

†Assume that the absorbent material becomes inactive at $\leq$ 8% H_2O

High Pressure (HP) Sodasorb, (S/S) ∿ 17% water - none bonded.

[B1] Naval Coastal Systems Laboratory Report 122-72, *Universal Humidity Chart*, by P. G. Sexton, June 1972.

†This is not actually a step function.

Estimates of Allowable H_2O Losses

Baralyme	$0.04 \frac{\text{lb } H_2O}{\text{lb absorbent}}$	$0.04 \frac{\text{gm } H_2O}{\text{gm absorbent}}$
HP Sodasorb	$0.09 \frac{\text{lb } H_2O}{\text{lb absorbent}}$	$0.09 \frac{\text{gm } H_2O}{\text{gm absorbent}}$

Therefore, the respective absorbent material is becoming inactive at a rate of:

Baralyme

$$(0.0042 \text{ lb } H_2O/\text{min})/(0.04 \text{ lb } H_2O/\text{lb}) = 1.05 \frac{\text{lb absorbent}}{\text{min}}$$

$$(1.903 \text{ gm } H_2O/\text{min})/(0.04 \text{ gm/gm}) = 47.6 \frac{\text{gm absorbent}}{\text{min}}$$

or

$$9.5 \frac{\text{min}}{\text{lb absorbent}} \quad (0.021 \frac{\text{min}}{\text{gm absorbent}})$$

HP Sodasorb

$$(0.0042 \text{ lb } H_2O/\text{min})/(0.09 \text{ lb } H_2O/\text{lb}) = 0.0467 \frac{\text{lb absorbent}}{\text{min}}$$

$$(1.903 \text{ gm } H_2O/\text{min})/(0.09 \text{ gm/gm}) = 21.18 \text{ gm} \frac{\text{absorbent}}{\text{min}}$$

or

$$21.42 \frac{\text{min}}{\text{lb absorbent}} \quad (0.047 \frac{\text{min}}{\text{gm absorbent}})$$

Approximate CO_2 Absorption Rates

From unpublished NCSC testing, Code 712, using canister gas vel ∿ 9.2 in/sec (∿ 23.37 cm/sec), amount of CO_2 absorbed at 0.5% SLE:

50°F (10.0°C) and 1 ATA

3 litres (105 ft^3) of 1% CO_2 in He per gram (0.0022 lb) HP Sodasorb

80°F (26.7°C) and 1 ATA

6 litres (0.212 ft^3) of 1% CO_2 in He per gram (0.0022 lb) Sodasorb

Ignoring what is absorbed in the first cold layer of absorbent material, consider the usage rate of the $80^{\circ}F$ ($26.7^{\circ}C$) zone to be approximated by:

6 litres ($0.212\ ft^3$) of 1% CO_2

0.06 litre ($0.0021186\ ft^3$) of CO_2 at $80^{\circ}F$ ($26.7^{\circ}C$)
where $\rho = 0.11224\ lb/ft^3$ ($\rho = 0.001798\ gm/cm^3$)

or,

$0.0021186\ ft^3$ ($60\ cm^3$) yields

$$0.1081 \frac{lb\ CO_2}{lb\ HP\ S/S} \quad 0.10788 \frac{gm\ CO_2}{gm\ HP\ S/S}$$

From OSF manned tests, upstream CO_2 levels are approximated by

$$\begin{array}{ll} \text{at } 50^{\circ}F\ (10.0^{\circ}C) & \left\{ \begin{array}{l} \text{Work: } 0.75\%\ SLE\ CO_2 \\ \text{Rest: } 0.33\%\ SLE\ CO_2 \end{array} \right. \\ \text{inlet temperature} & \end{array}$$

Using the higher work rate at 1 ATA:

$$(6\ ACFM)\ (0.75\%) \longrightarrow (6\ ft^3/min)(0.0075) = 0.045\ ft^3 CO_2\ min.$$
$$((169.92\ LPM)\ (0.75\%) \quad (169.92)\ (0.0075) = 1.274\ litre\ CO_2/min)$$

where at $50^{\circ}F$ ($10.0^{\circ}C$) and 1 ATA for CO_2

$\rho = 0.11897\ lb\ CO_2/ft^3$ yields $0.00535\ lb\ CO_2/min.$

$\rho = 1.9057\ gm/litre$ yields $24.286\ gm\ CO_2\ min.$

or

$0.1081\ lb\ CO_2/lb\ HP\ S/S\ /\ 0.00535\ lb\ CO_2/min =$

$(0.10788\ gm\ CO_2/gm\ HP\ S/S\ /\ 2.4286\ gm\ CO_2/min) =$

20.21 min/lb HP S/S or 0.0495 lb HP S/S/min

(0.004442 min/gm HP S/S or 22.51 gm HP S/S/min)

Consumption Rate

For lack of a better approximation, consider baralyme and high pressure sodasorb to have the same consumption rates (0.0495 lb. absorbent/min) (22.5 gm absorbent/min). From empirical tests, the real rate for baralyme should reflect shorter durations.

Compare

1. Rate at which absorbent material is being used by absorbing CO_2: 0.0495 lb/min (22.51 gm/min)

2. Rate at which absorbent material is being dried beyond a useable level:

   a. Baralyme 0.105 lb/min (47.63 gm/min)

   b. HP Sodasorb 0.0467 lb/min (21.18 gm/min)

Conclusions

1. Comparing the usage rate (1 above) and the drying rate for baralyme (2 above) indicates that the absorbent is becoming too dry to react faster than it is being used. This comparison correlates with experiments.

2. The usage rate with high pressure sodasorb (2 above) is higher than the drying rate (1 above) indicating that the drying rate will not directly terminate the reaction; however, a possible reduction in absorption efficiency is still possible due to excessive moisture in the lower canister towards the end of its duration.

APPENDIX C

MK 12 SSDS MANNED HOT WATER HEATED RECIRCULATOR DURATION TEST RESULTS

As described in the section on M12 scrubber development, the MK 12 recirculator demonstrated consistent, long canister duration. In this configuration, a hot water flow was directed at the recirculator inlet/outlet hoses and then exhausted into the recirculator case/shrouds (Figure C-1 for thermistor placement). This flow path and temperature distribution produced conditions conducive to desired CO_2 scrubbing action using high performance, medical-grade sodasorb and baralyme at various temperatures. The modified recirculator demonstrated the required 9-hour duration in water temperatures above 50°F (10.0°C) without hot water heating. A summary of backpack temperatures for the MK 12 test series is shown in Table C1.

Dive profiles of the manned canister life tests are contained in this Appendix. Each plot shows time versus CO_2 level (%SLE). Refer to Table 8 in the report for a summary of the test results.

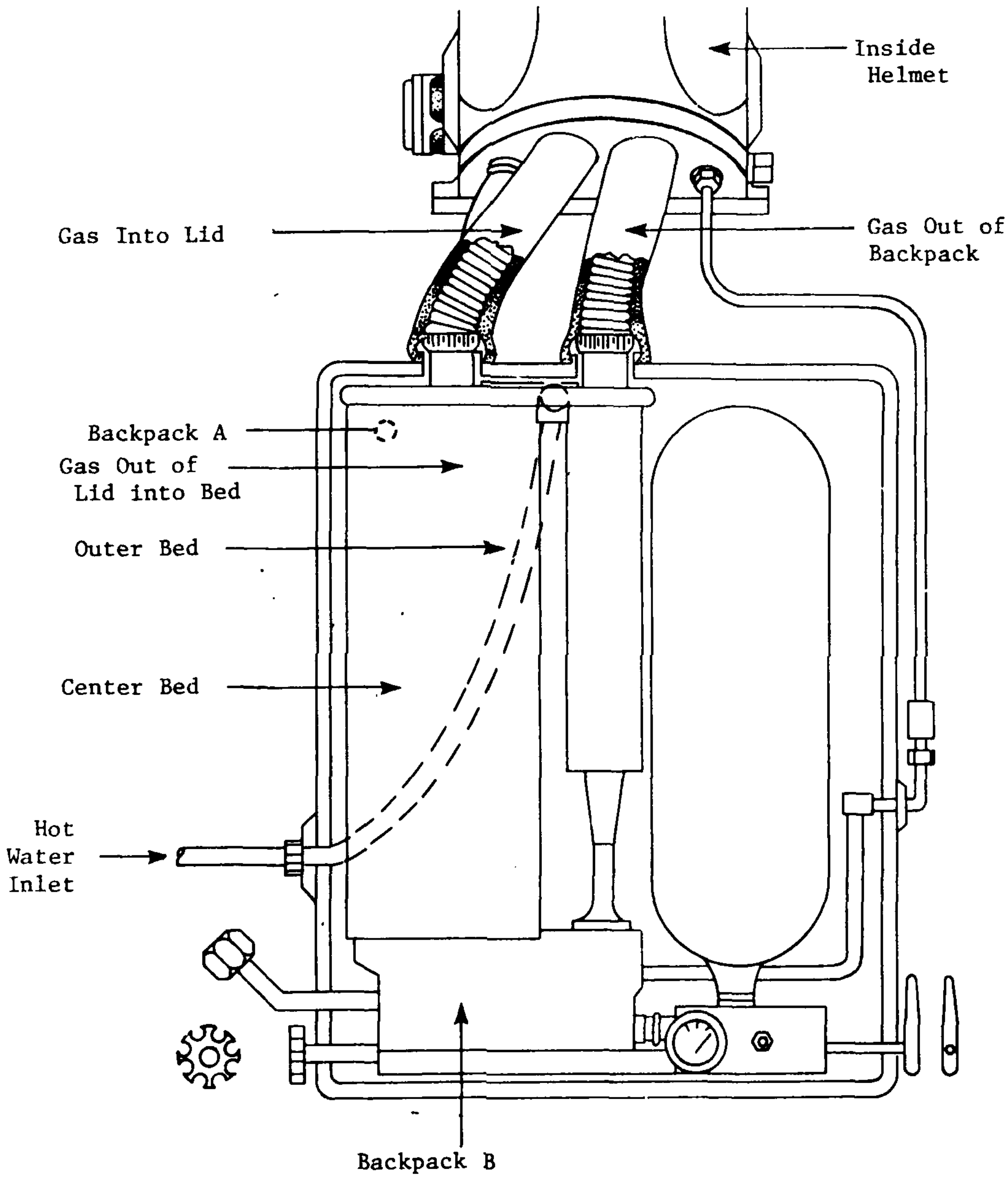


FIGURE C1. THERMISTOR PLACEMENT, MK 12 SSDS MIXED-GAS RECIRCULATOR

LEGEND

1st Row-Mean Temperature Readings
2nd Row-Variance Readings

TABLE C1

BACKPACK TEMPERATURES - MK 12 SSDS MANNED CANISTER DURATION TESTS

(Sheet 1 of 3)

DATE/TEST #*	CENTER BED C°/F°	OUTER BED C°/F°	GAS OUT OF EJECTOR C°/F°	GAS INTO CANISTER C°/F°	INSIDE HELMET C°/F°	BACK PACK A C°/F°	BACK PACK B C°/F°	HOT WATER AT OUTLET C°/F°	BATH TEMP C°/F°	OUT LID INTO BED C°/F°
12/20/77	20.51 68.92 7.24 13.03	20.00 68.00 5.61 10.10	18.56 65.41 5.64 10.15	15.83 60.49 7.03 12.65	14.89 58.80 6.64 11.95	17.00 62.60 8.95 16.11	17.65 63.77 9.80 17.64		20.05 68.09 11.26 20.27	
1/16/78	20.01 68.02 11.20 20.16	20.57 69.03 10.83 19.49	20.80 69.44 10.68 19.22	20.25 68.45 10.69 19.24	19.93 67.87 10.55 18.99	21.10 69.98 11.90 21.42	20.84 69.51 11.58 20.84	21.37 70.47 11.80 21.24	20.71 69.28 12.06 21.71	
1/19/78 #72	21.55 70.79 13.02 23.44	21.77 71.19 12.96 23.33	21.94 71.49 12.88 23.18	21.80 71.24 12.77 22.99	21.68 71.02 12.66 22.79	22.02 71.64 12.77 22.99	22.18 71.92 12.72 22.90	22.57 72.63 12.90 23.22	22.19 71.94 13.04 23.47	
1/20/78	21.00 69.80 11.92 21.46	21.27 70.29 11.79 21.22	21.21 70.18 11.61 20.90	20.71 69.28 11.64 20.95	20.43 68.77 11.50 20.70	20.79 69.42 11.57 20.83	20.77 69.39 11.46 20.63		20.59 69.06 11.92 21.46	21.20 70.16 11.65 20.97
1/23/78 #74	20.82 69.48 13.49 24.28	20.98 69.76 13.31 23.96	21.18 70.12 13.18 23.72	20.92 69.66 13.06 23.51	20.75 69.35 12.90 23.22	21.01 69.82 12.88 23.18	21.24 70.23 12.83 23.09	21.73 71.11 13.04 23.47	21.24 70.23 13.20 23.76	
1/24/78 #75	20.91 69.64 11.83 21.29	21.19 70.14 11.72 21.10	21.25 70.25 11.54 20.77	20.84 69.51 11.57 20.83	20.62 69.12 11.46 20.63	20.85 69.53 11.37 20.47	21.14 70.05 11.34 20.41	21.22 70.20 11.20 20.16	20.54 68.97 11.47 20.65	21.36 70.45 11.08 19.94
1/25/78 #76	20.85 69.53 11.36 20.45	20.98 69.76 11.27 20.29	21.39 70.50 14.15 25.47	21.11 70.00 14.13 25.43	20.94 69.69 14.03 25.25	21.02 69.84 13.89 25.00	21.04 69.87 13.78 24.80	21.06 69.91 13.65 24.57	20.59 69.06 13.65 24.57	20.93 69.67 13.55 24.39

*AS APPLICABLE

LEGEND

1st Row-Mean Temperature Readings
2nd Row-Variance Readings

TABLE C1

BACKPACK TEMPERATURES - MK 12 SSDS MANNED CANISTER DURATION TESTS

(Sheet 2 of 3)

DATE/TEST #*	CENTER BED C°/F°	OUTER BED C°/F°	GAS OUT OF EJECTOR C°/F°	GAS INTO CANISTER C°/F°	INSIDE HELMET C°/F°	BACK PACK A C°/F°	BACK PACK B C°/F°	HOT WATER AT OUTLET C°/F°	BATH TEMP C°/F°	OUT LID INTO BED C°/F°
1/26/78 #77	29.03 84.25 1.80 3.24	26.89 80.40 2.39 4.30	26.22 79.20 1.14 2.05	23.26 73.87 1.92 3.46	14.82 58.68 0.95 1.71	18.67 65.61 0.99 1.78	18.02 64.44 4.43 7.97	28.59 83.46 0.77 1.39	3.12 37.62 0.22 0.40	22.75 72.95 2.41 4.34
1/30/78 #78	27.42 81.36 1.34 2.41	25.65 78.17 1.51 2.72	28.08 82.54 1.23 2.21		13.62 56.52 1.11 2.00	26.97 80.55 1.63 2.93	20.54 68.97 5.31 9.56	30.50 86.90 0.55 0.99	3.52 38.34 0.21 0.38	20.17 68.31 3.20 5.76
1/31/78 #79	29.35 84.83 1.79 3.22	29.45 85.01 1.63 2.93	29.40 84.92 1.86 3.35		14.89 58.80 1.34 2.41	28.00 82.40 2.54 4.57	8.10 46.58 1.08 1.94	37.10 98.78 2.49 4.48	3.85 38.93 8.36 0.65	27.07 80.73 1.89 3.40
2/01/78 #80	24.49 76.08 8.61 15.50	24.52 76.14 6.76 12.17	23.46 74.23 8.09 14.56		16.69 62.04 2.71 4.88	21.43 70.57 7.15 12.87	17.56 63.61 5.76 10.37	24.40 75.92 9.55 17.19	9.94 49.89 0.71 1.28	19.68 67.42 6.53 11.75
2/02/78 #81	22.41 72.34 4.63 8.33	19.81 67.66 5.46 9.83	15.76 60.37 7.13 12.83		14.54 58.17 2.90 5.22	14.35 57.83 6.39 11.50	12.27 54.09 4.18 7.52	15.69 60.24 8.62 15.52	9.84 49.71 0.76 1.37	13.54 56.37 5.38 9.68
2/06/78 #83	24.74 76.53 6.05 10.89	25.28 77.50 2.34 4.21	26.17 79.11 1.73 3.11		14.56 58.21 2.35 4.33	24.42 75.96 1.59 2.86	17.81 64.06 4.47 8.05	28.88 83.98 0.70 1.26	16.47 61.65 12.52 22.54	21.44 70.59 1.84 3.31
2/07/78 #84	29.56 85.21 3.19 5.74	29.65 85.37 3.17 5.71	33.91 93.04 2.60 4.68		15.84 60.51 2.24 4.03	28.89 84.00 1.96 3.53	20.78 69.40 10.05 18.09	39.60 103.28 1.14 2.05	3.81 38.86 0.15 0.27	29.43 84.97 2.26 4.07

* AS APPLICABLE

LEGEND

1st Row-Mean Temperature Readings
2nd Row-Variance Readings

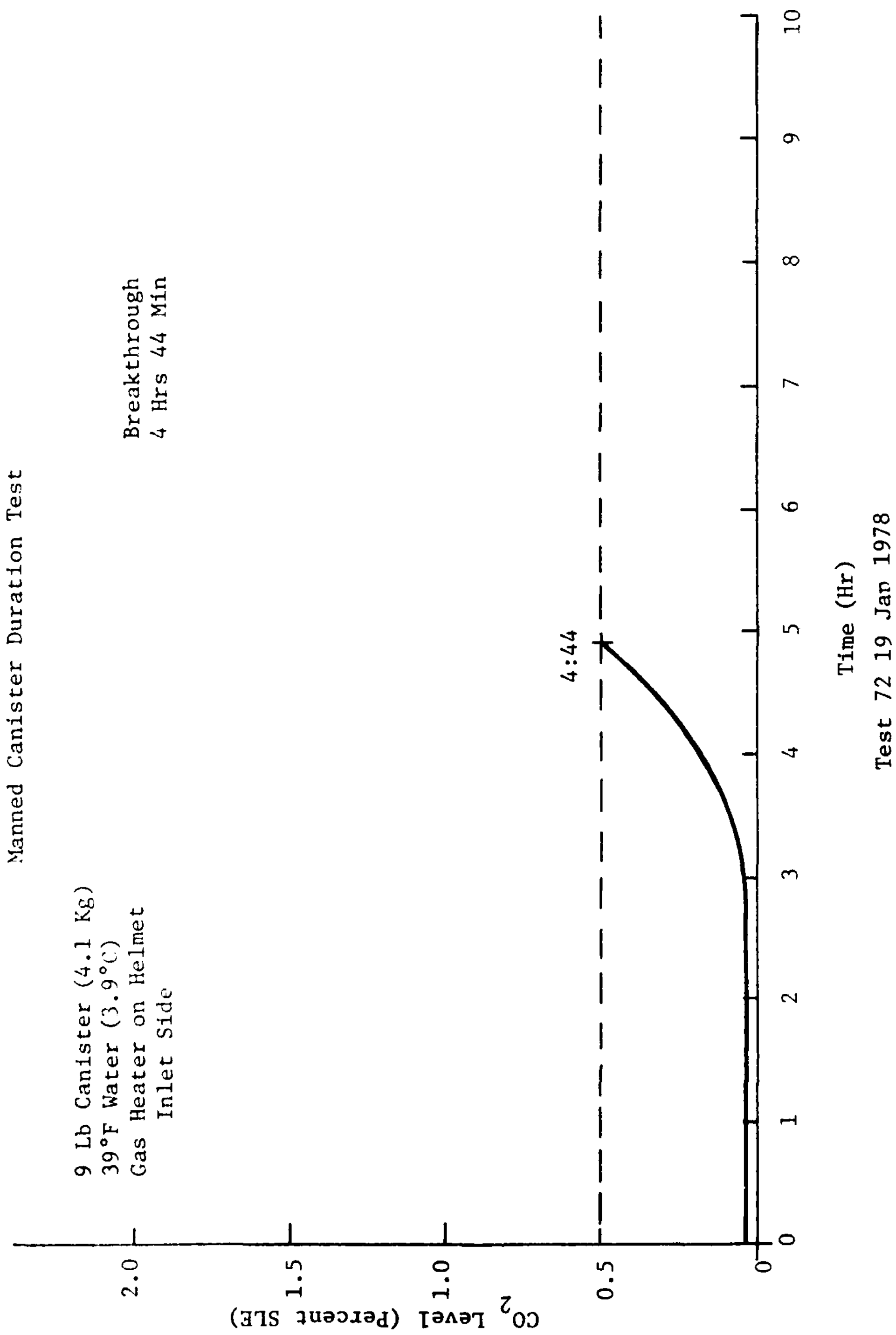
TABLE C1

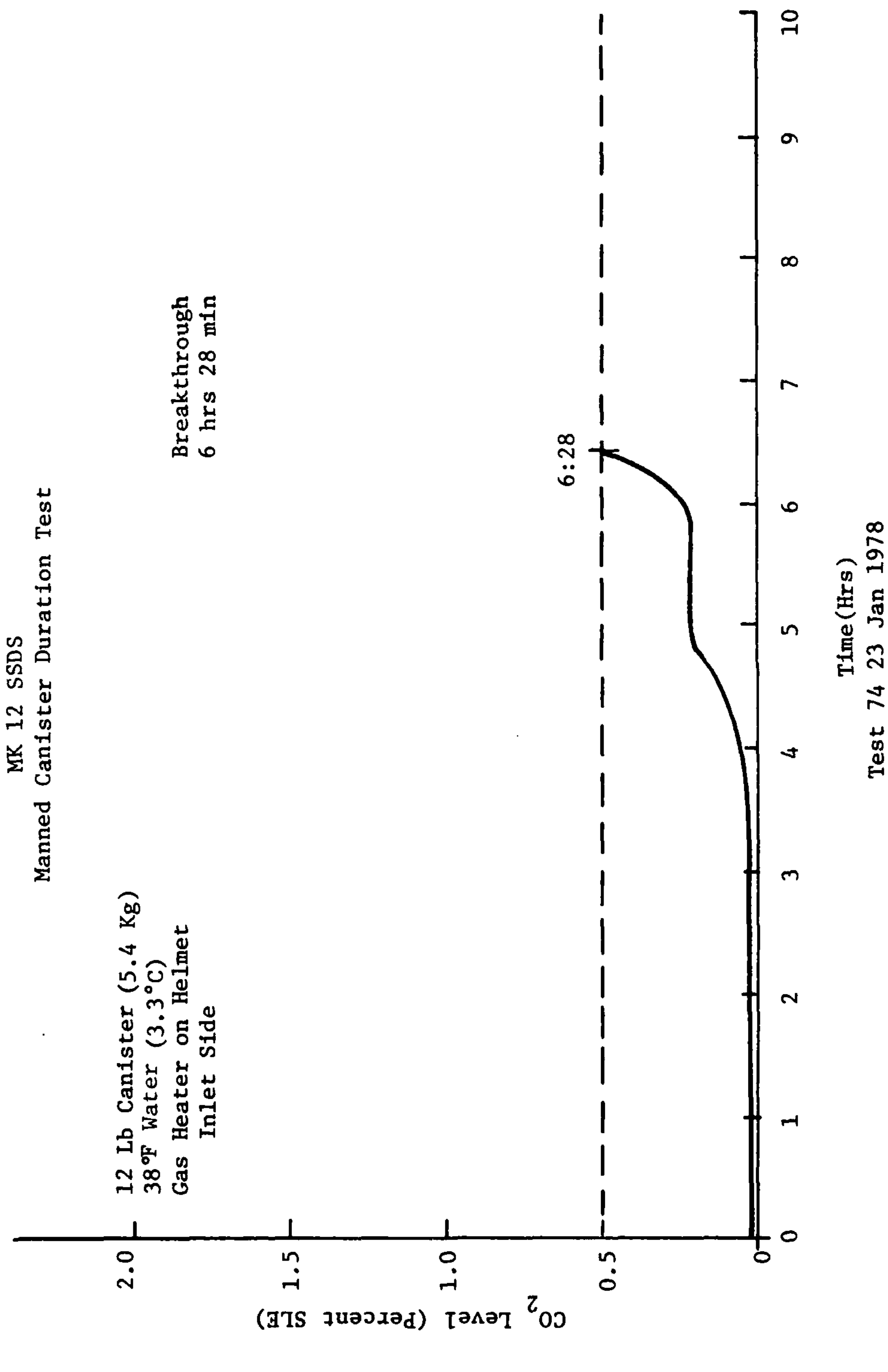
BACKPACK TEMPERATURES - MK 12 SSDS MANNED CANISTER DURATION TESTS

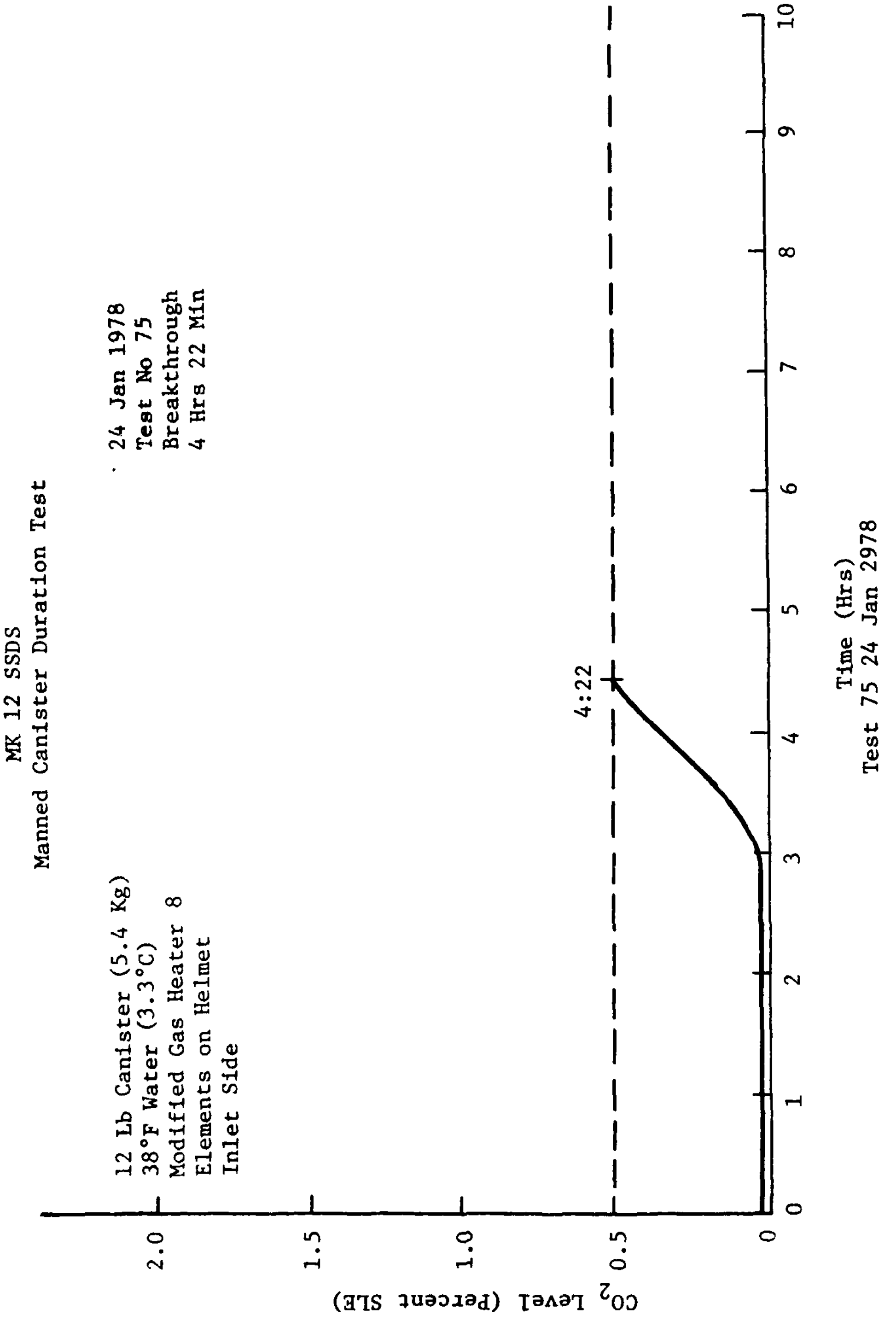
(Sheet 3 of 3)

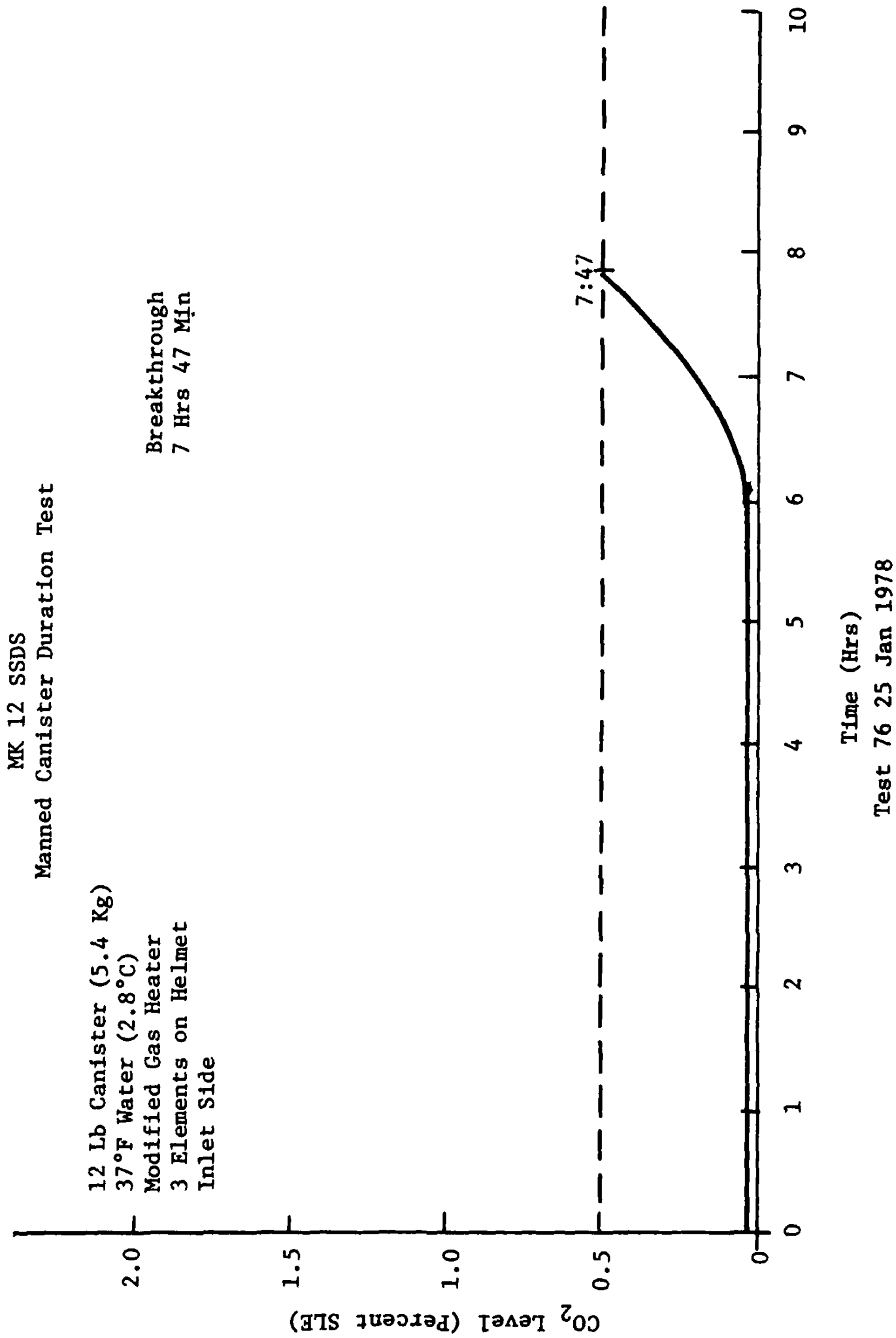
DATE/TEST #*	CENTER BED C°/F°	OUTER BED C°/F°	GAS OUT OF EJECTOR C°/F°	GAS INTO CANISTER C°/F°	INSIDE HELMET C°/F°	BACK PACK A C°/F°	BACK PACK B C°/F°	HOT WATER AT OUTLET C°/F°	BATH TEMP C°/F°	OUT LID INTO BED C°/F°
2/08/78 #85	11.16 52.09 4.28 7.70	15.91 60.64 1.72 3.10	10.62 51.12 0.76 1.37		12.21 53.98 1.31 2.36	10.64 51.15 1.94 3.49	9.33 48.79 0.95 1.71	9.23 48.61 0.94 1.69	9.08 48.34 0.96 1.73	10.24 50.43 0.89 1.60
2/09/78 #86	19.18 66.52 0.71 1.28	17.61 63.70 1.77 3.19	12.11 53.80 0.50 0.90		12.96 55.33 0.62 1.12	10.59 51.06 0.12 0.22	10.53 50.95 0.17 0.31	10.78 51.40 0.24 0.43	9.96 49.93 0.08 0.14	11.81 53.26 0.23 0.41
2/10/78 #87	11.13 52.03 4.47 8.05	16.55 61.79 1.67 3.01	12.37 54.27 0.22 0.40		12.63 54.73 0.91 1.64	12.21 53.98 1.09 1.96	10.72 51.30 0.21 0.38	10.93 51.61 0.26 0.47	10.41 50.74 0.11 0.20	12.18 53.92 0.29 0.52
2/13/78 #88	31.75 89.15 1.90 3.42	29.98 85.96 2.23 4.01	25.25 77.45 1.41 2.54		25.89 78.60 1.77 3.19	24.74 76.53 1.92 3.46	23.83 74.89 1.54 2.77	24.27 75.69 1.57 2.83	24.35 75.83 2.25 4.05	25.21 25.21 1.66 2.99
2/15/78	13.12 55.62 1.21 2.18	11.42 52.56 1.58 2.85	0.92 33.66 0.16 0.30		3.07 37.52 1.03 1.86	1.12 34.02 0.30 0.55	-0.46 31.17 1.33 2.39	-0.04 31.93 0.09 0.16	-2.14 28.15 0.09 0.16	0.50 32.90 0.16 0.28
2/16/78 #91	30.58 87.04 2.06 3.71	34.86 94.76 4.11 7.40	31.71 89.07 1.89 3.39		11.44 52.58 1.06 1.90	28.94 84.08 2.25 4.05	16.77 62.18 4.69 8.43	35.31 95.57 2.21 3.98	1.22 34.19 1.58 2.84	30.21 86.37 2.51 4.52

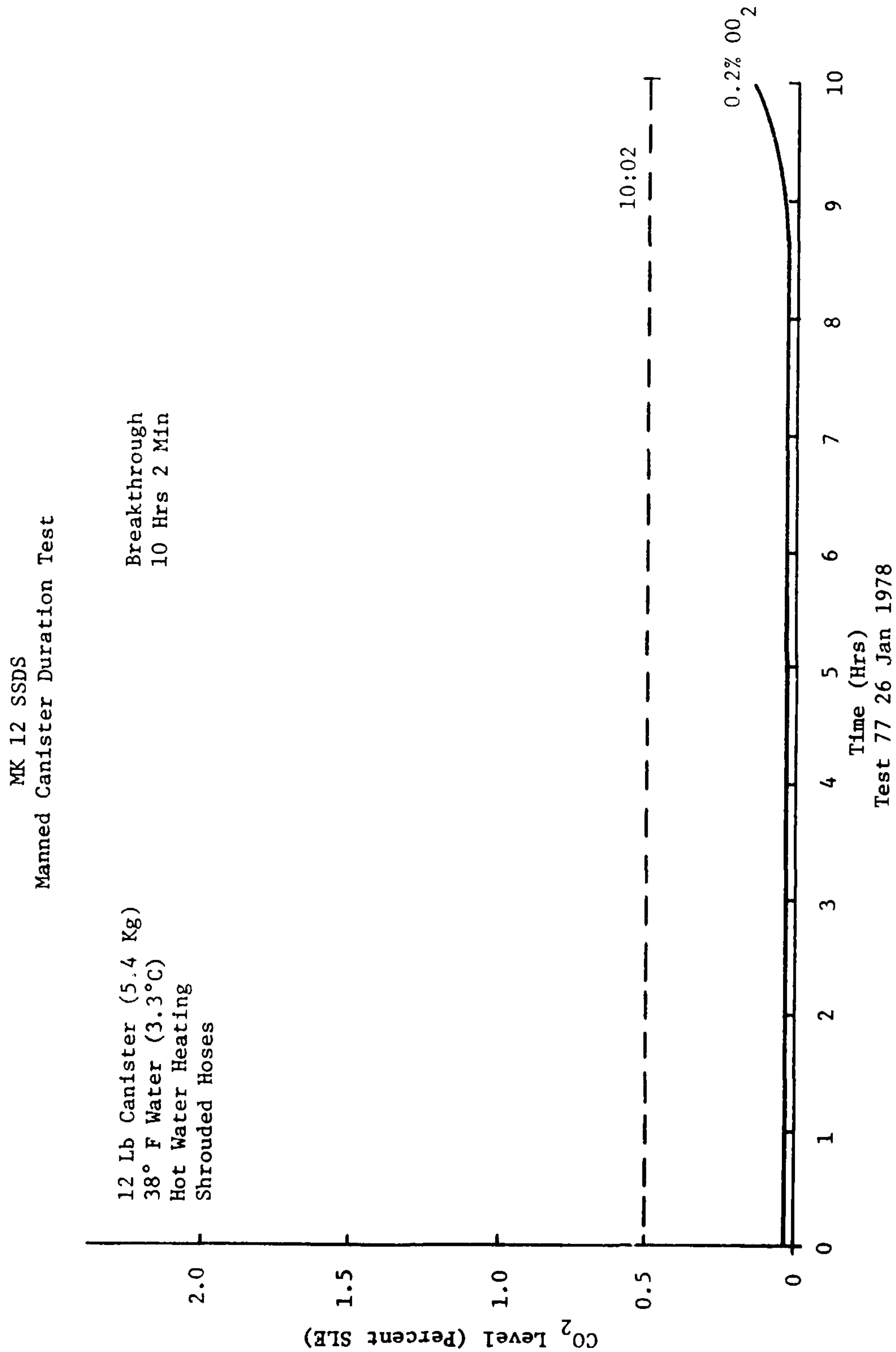
* AS APPLICABLE

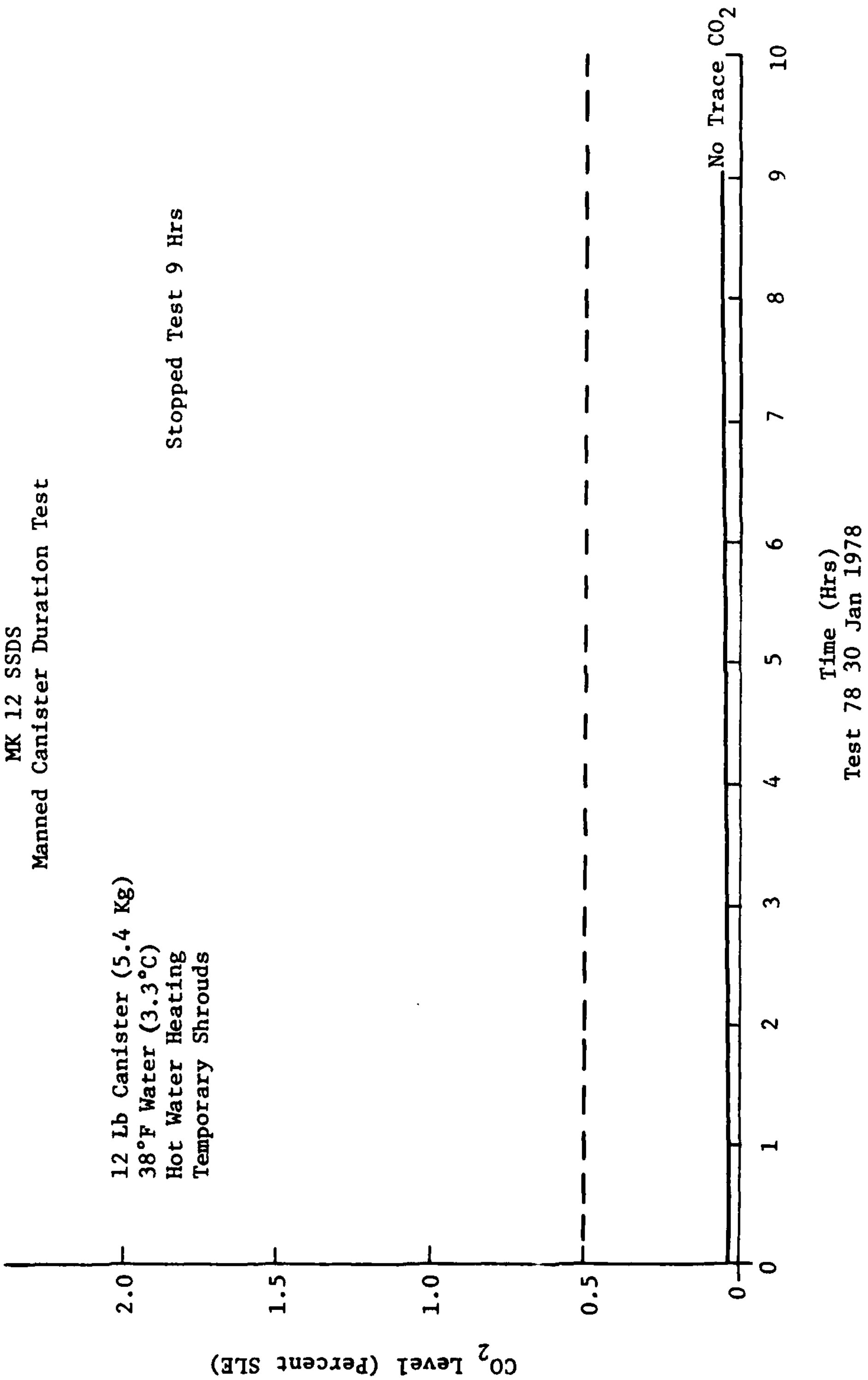

MK 12 SSDS
Manned Canister Duration Test
9 Lb Canister (4.1 Kg)
39°F Water (3.9°C)
Gas Heater on Helmet
Inlet Side
Breakthrough
4 Hrs 44 Min
4:44
CO_2 Level (Percent SLE)
0
0.5
1.0
1.5
2.0
0
1
2
3
4
5
6
7
8
9
10
Time (Hr)
Test 72 19 Jan 1978

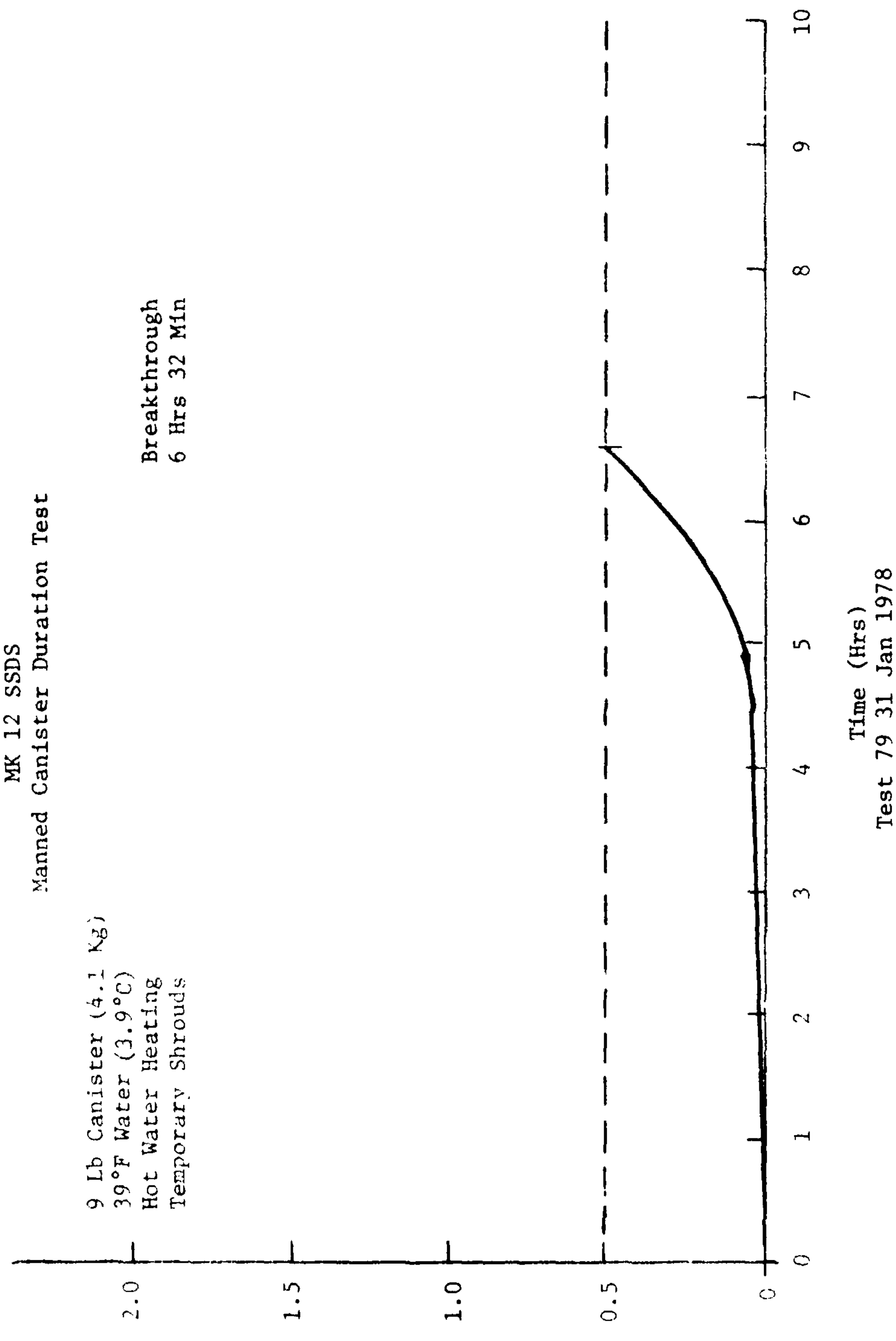

MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
38°F Water (3.3°C)
Gas Heater on Helmet
Inlet Side
Breakthrough
6 hrs 28 min
6:28
CO_2 Level (Percent SLE)
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time(Hrs)
Test 74 23 Jan 1978

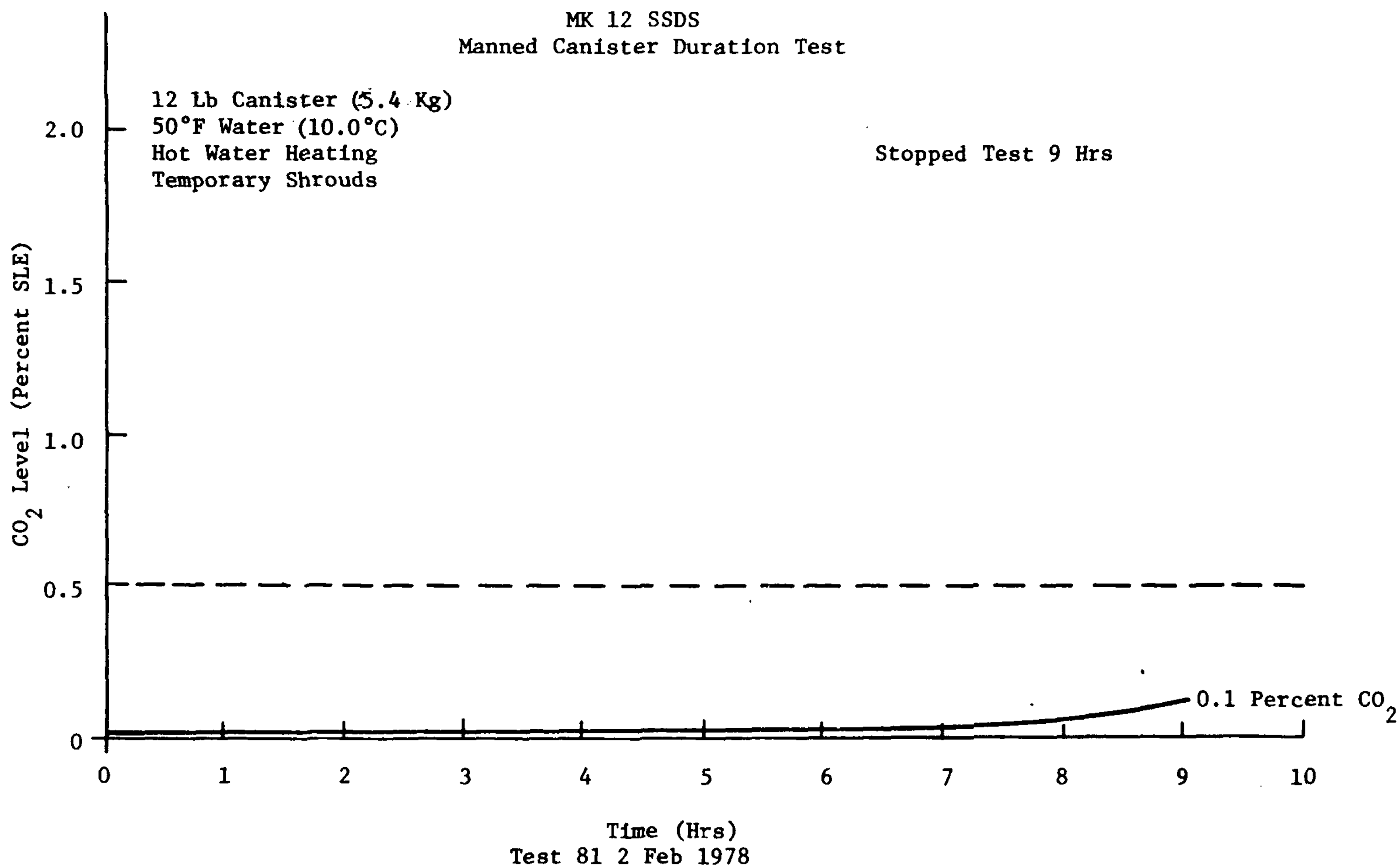

MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
38°F Water (3.3°C)
Modified Gas Heater 8
Elements on Helmet
Inlet Side
24 Jan 1978
Test No 75
Breakthrough
4 Hrs 22 Min
4:22
CO_2 Level (Percent SLE)
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 75 24 Jan 2978

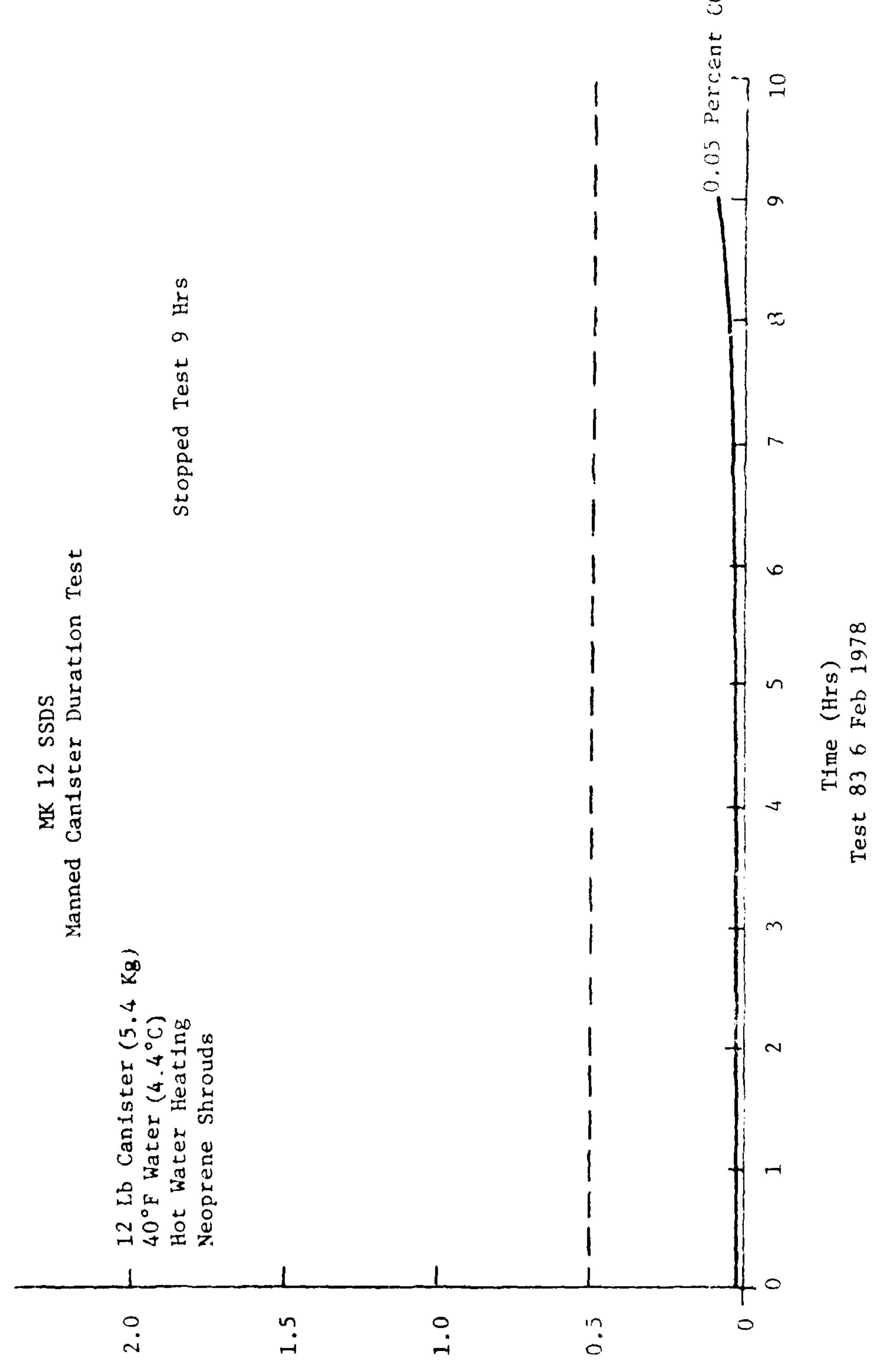

MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
37°F Water (2.8°C)
Modified Gas Heater
3 Elements on Helmet
Inlet Side
Breakthrough
7 Hrs 47 Min
7:47
2.0
1.5
1.0
0.5
0
CO_2 Level (Percent SLE)
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 76 25 Jan 1978


MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
38° F Water (3.3°C)
Hot Water Heating
Shrouded Hoses
Breakthrough
10 Hrs 2 Min
10:02
0.2% CO_2
CO_2 Level (Percent SLE)
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 77 26 Jan 1978


MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
38°F Water (3.3°C)
Hot Water Heating
Temporary Shrouds
Stopped Test 9 Hrs
No Trace CO2
0
0.5
1.0
1.5
2.0
CO2 Level (Percent SLE)
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 78 30 Jan 1978


MK 12 SSDS
Manned Canister Duration Test
9 Lb Canister (4.1 Kg)
39°F Water (3.9°C)
Hot Water Heating
Temporary Shrouds
Breakthrough
6 Hrs 32 Min
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 79 31 Jan 1978


MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
50°F Water (10.0°C)
Hot Water Heating
Temporary Shrouds
Stopped Test 9 Hrs
0.1 Percent CO2
CO2 Level (Percent SLE)
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 81 2 Feb 1978


MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
40°F Water (4.4°C)
Hot Water Heating
Neoprene Shrouds
Stopped Test 9 Hrs
0.05 Percent CO_2
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 83 6 Feb 1978

AD-A092 314 NAVAL COASTAL SYSTEMS CENTER PANAMA CITY FL F/G 6/11

MK 11 AND MK 12 CO2 SCRUBBER DEVELOPMENT.(U)

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2 OF 2

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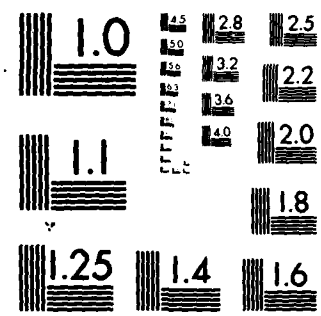
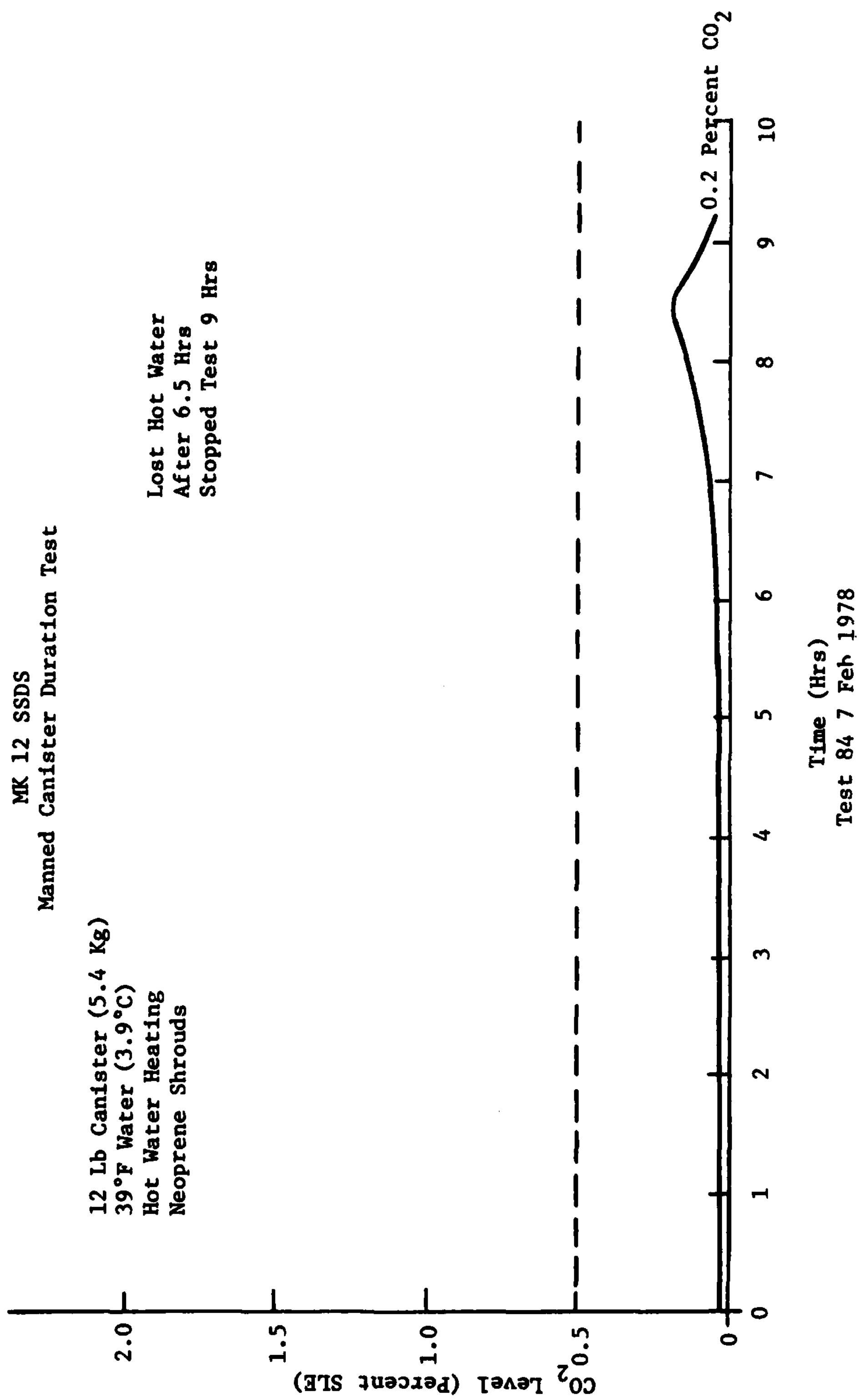
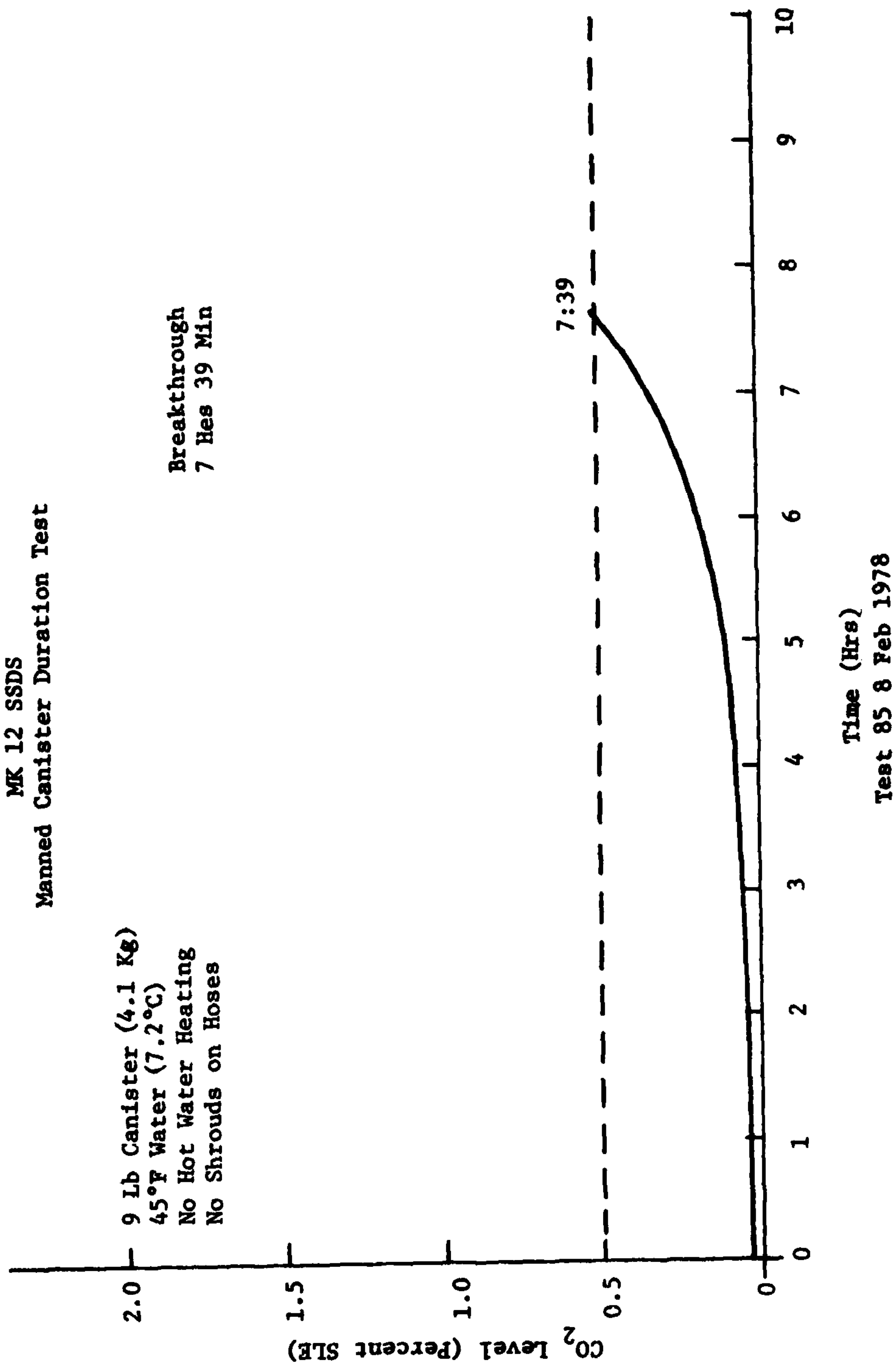
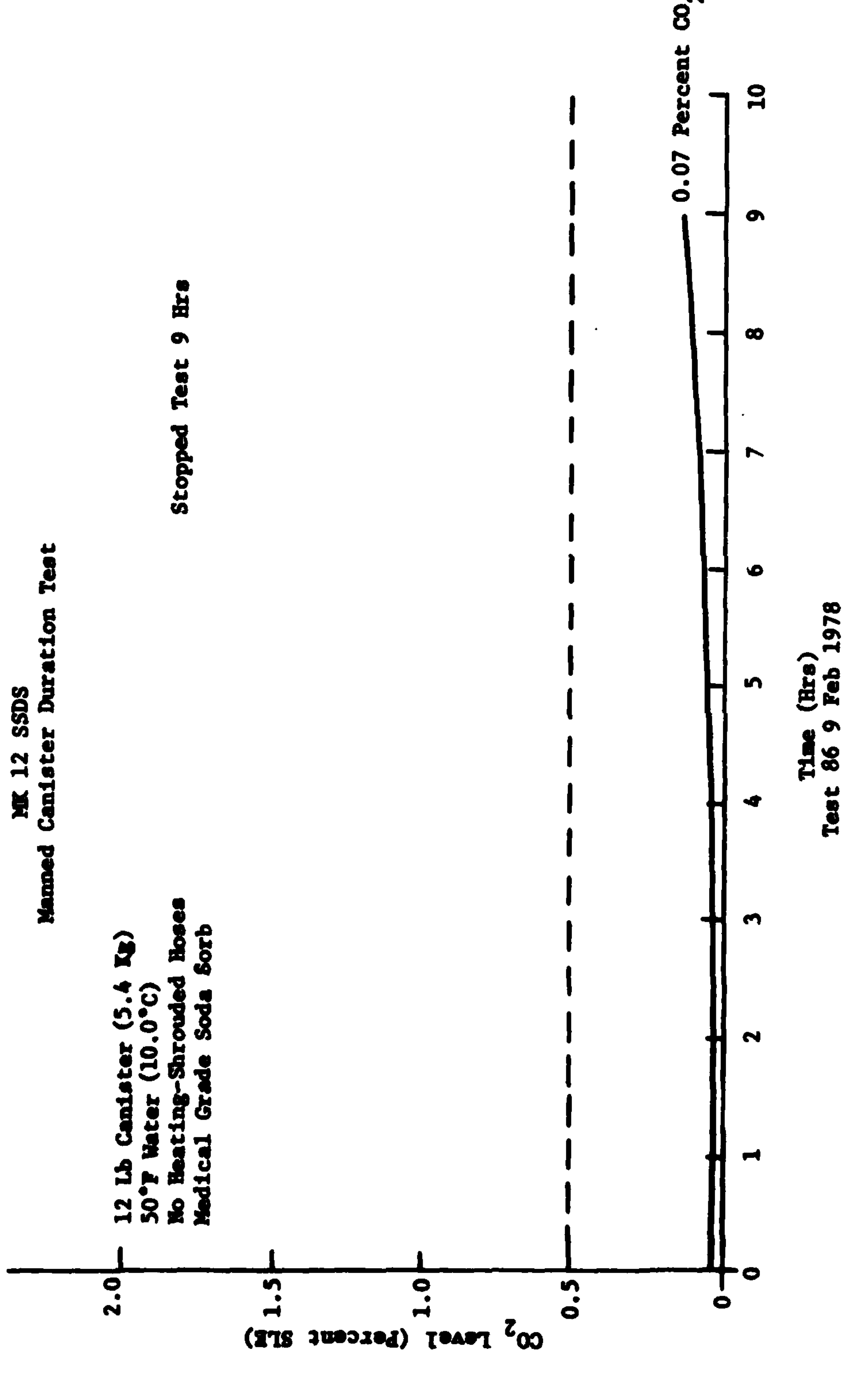
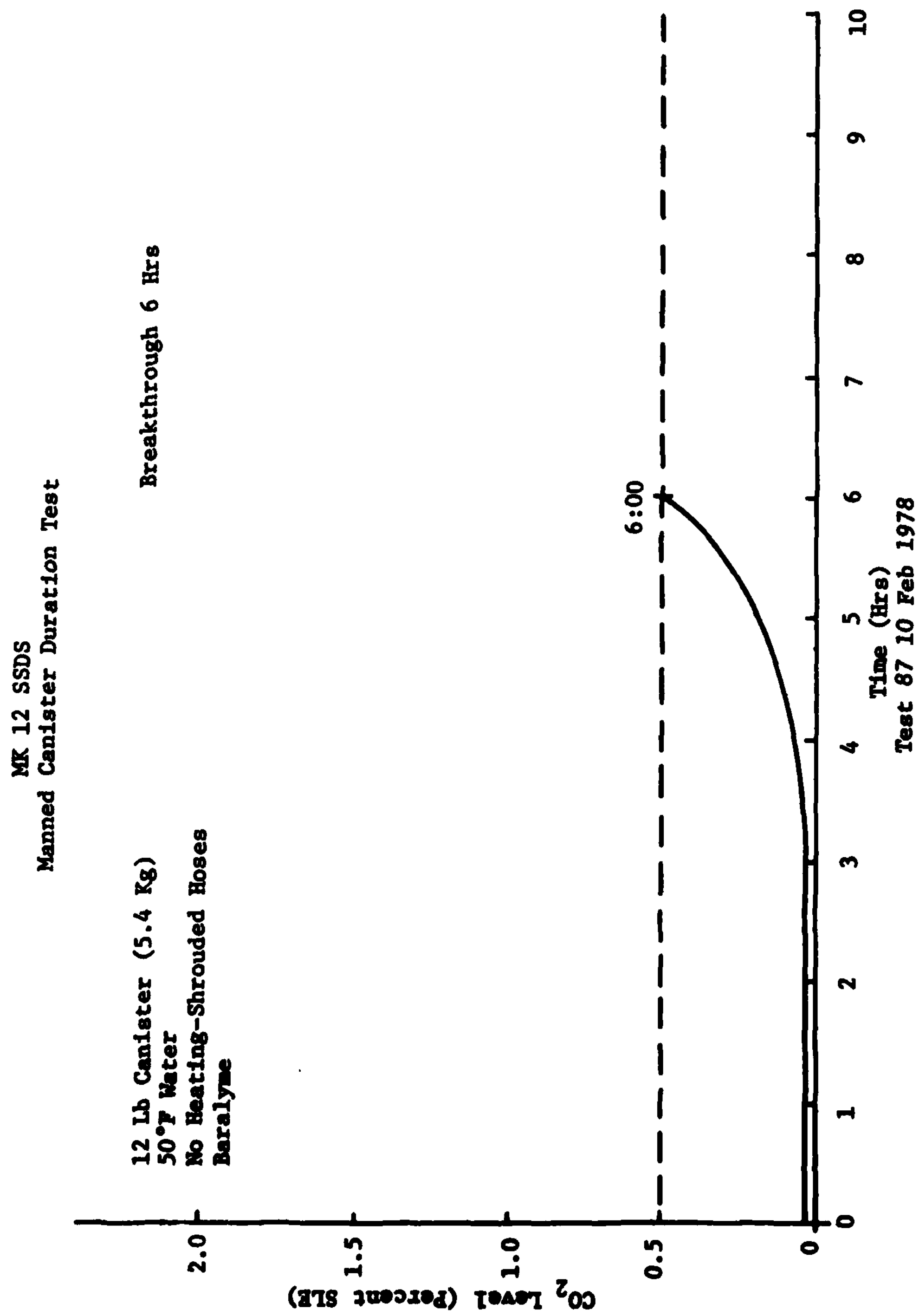


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

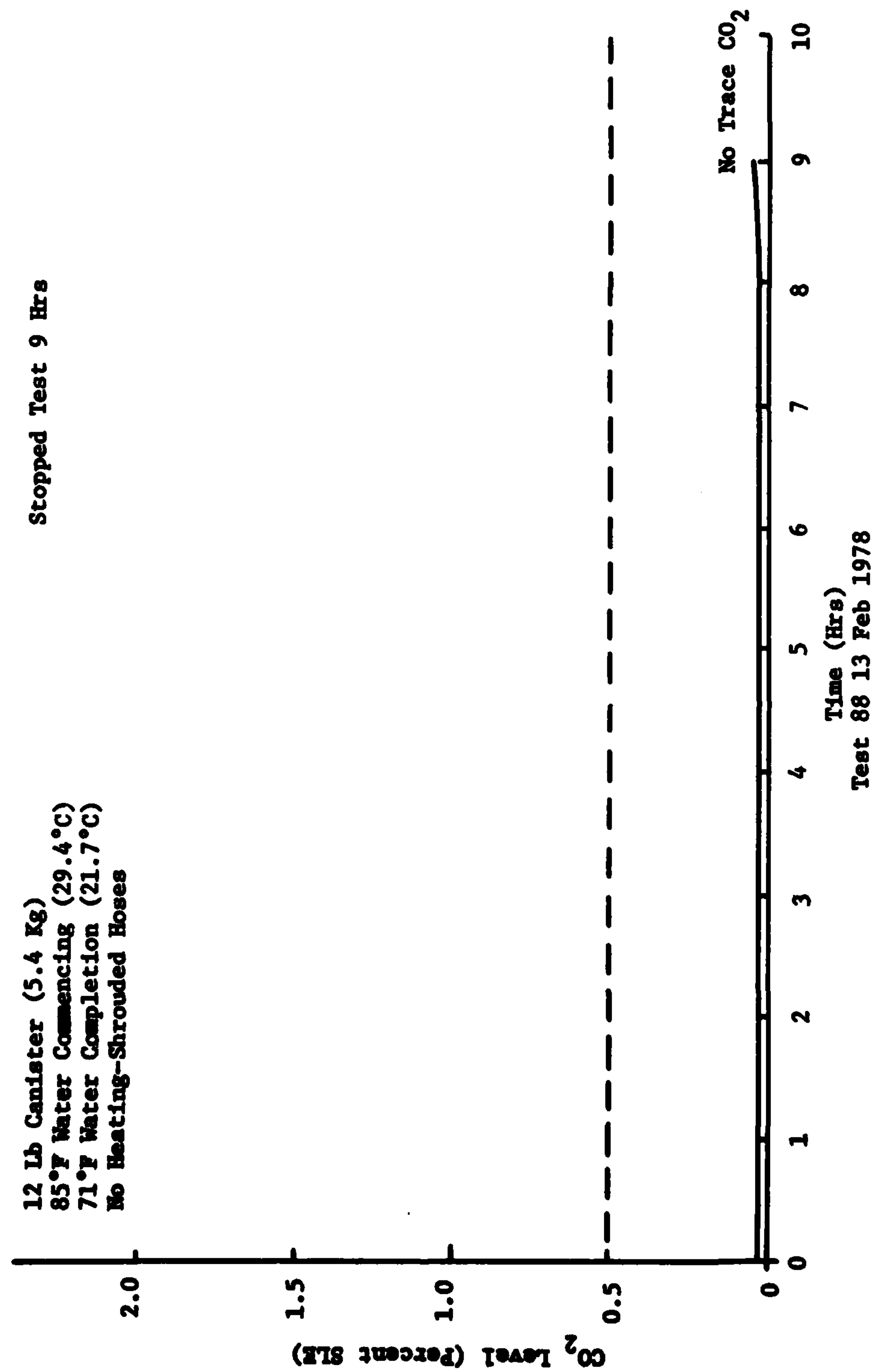

MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
39°F Water (3.9°C)
Hot Water Heating
Neoprene Shrouds
Lost Hot Water
After 6.5 Hrs
Stopped Test 9 Hrs
0.2 Percent CO_2
CO_2 Level (Percent SLE)
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 84 7 Feb 1978


MK 12 SSDS
Manned Canister Duration Test
9 Lb Canister (4.1 Kg)
45°F Water (7.2°C)
No Hot Water Heating
No Shrouds on Hoses
Breakthrough
7 Hes 39 Min
7:39
2.0
1.5
1.0
0.5
0
CO_2 Level (Percent SLE)
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 85 8 Feb 1978

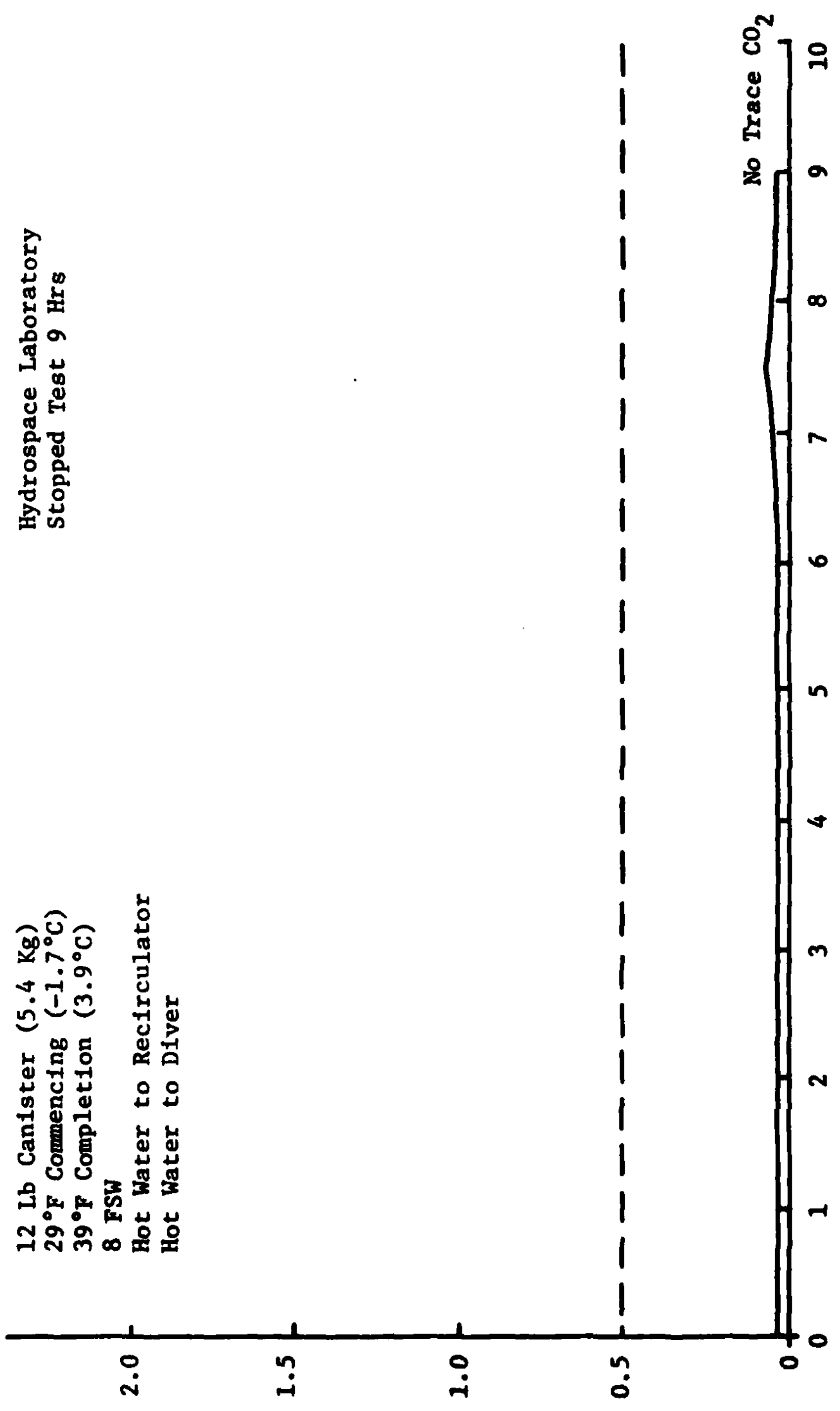

MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
50°F Water (10.0°C)
No Heating-Shrouded Hoses
Medical Grade Soda Sorb
Stopped Test 9 Hrs
0.07 Percent CO_2
2.0
1.5
1.0
0.5
0
CO_2 Level (Percent SLE)
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 86 9 Feb 1978


MK 12 SSDS
Manned Canister Duration Test
Breakthrough 6 Hrs
12 Lb Canister (5.4 Kg)
50°F Water
No Heating-Shrouded Hoses
Baralyme
6:00
CO_2 Level (Percent SLE)
0
0.5
1.0
1.5
2.0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 87 10 Feb 1978

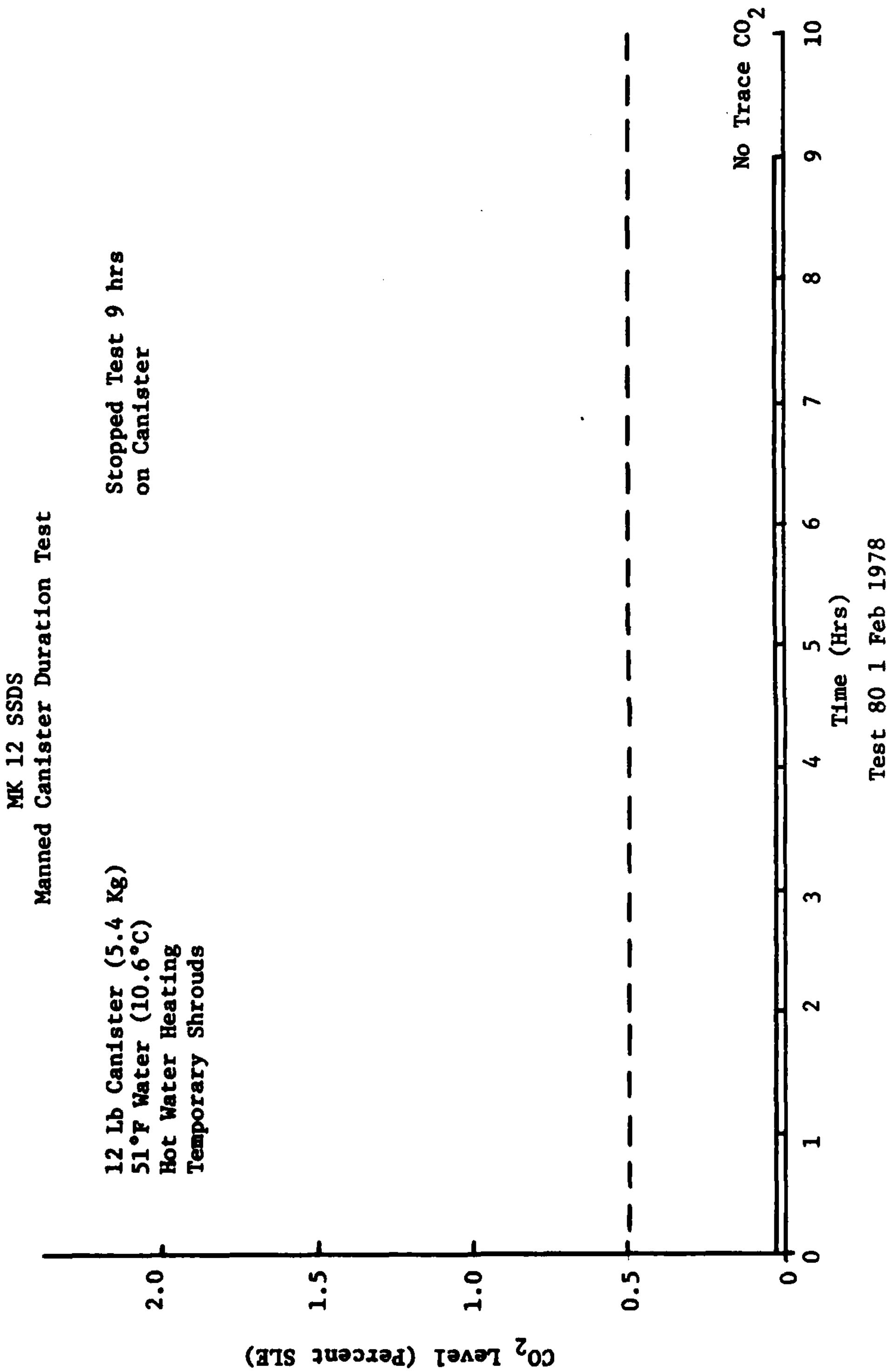
MK 12 SSDS
Manned Canister Duration Test



MK 12 SSDS
Manned Cold Water Duration Test



Time (Hrs)
Test 91 16 Feb 1978


MK 12 SSDS
Manned Canister Duration Test
12 Lb Canister (5.4 Kg)
51°F Water (10.6°C)
Hot Water Heating
Temporary Shrouds
Stopped Test 9 hrs
on Canister
No Trace CO_2
CO_2 Level (Percent SLE)
2.0
1.5
1.0
0.5
0
0
1
2
3
4
5
6
7
8
9
10
Time (Hrs)
Test 80 1 Feb 1978

END

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